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Impacts of varying building geometries, materials and technologies on the performance of buildings

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Resumo

O consumo de energia em edifícios corresponde a aproximadamente 40% da energia final consumida na União Europeia. Os edifícios representam uma importância vital no quotidiano dos seres humanos, uma vez que passamos a maior parte do nosso tempo no espaço interior. As características de um edifício não só definem o seu consumo energético, mas também influenciam a produtividade e o bem-estar dos seus ocupantes. Com a construção de novos edifícios ou a renovação dos existentes com elevados standards de performance energética, é possível provar que a mitigação das alterações climáticas e a melhoria na qualidade de vida podem ser alcançadas em simultâneo. O propósito é contribuir com soluções para uma sociedade que está cada vez mais consciente da necessidade de adotar um modo de vida eficiente e sustentável. Dada esta realidade, os edifícios devem seguir um desenvolvimento num caminho de consumo neto de energia nulo, através da integração de materiais, tecnologias e fontes de energia não convencional que contribuam para uma redução de impacto ambiental e emissões de gases com efeito de estufa.

Este projeto foca-se na avaliação do consumo energético associado à garantia de condições de conforto térmico dos ocupantes. Em edifícios de escritórios com sistema AVAC, o consumo de energia deste tipo de sistemas pode chegar a representar um quarto do total consumido no edifício. Deste modo, diversos conceitos de edifício foram desenvolvidos com o intuito de avaliar o seu impacto no consumo de energia AVAC e ainda na capacidade dos equipamentos, com respetivas consequências no custo de energia e no investimento em equipamentos. Estes conceitos de edifício foram construídos tendo em conta uma configuração específica que inclui estrutura, materiais de construção, equipamentos AVAC e outras tecnologias que fornecem eletricidade ao edifício. Adicionalmente, foram analisados fatores externos que influenciam a performance energética, nomeadamente efeitos de interação entre edifícios e alterações climáticas. Os outputs resultantes da análise – feita através do programa de simulação em edifícios IDA ICE – do comportamento térmico dinâmico dos conceitos de edifício foram traduzidos em indicadores de performance energéticos, de sustentabilidade e económicos. Indicadores de energia são usados para avaliar o consumo (e a produção) de energia de um edifício, enquanto que os indicadores de sustentabilidade analisam o impacto que um edifício tem no ambiente ao seu redor e os indicadores económicos estudam a rentabilidade de medidas de renovação ou o investimento realizado em novos projetos. Assim, os utilizadores (ou clientes) dispõem de um vasto leque de informação que lhes permite fazer uma escolha consciente e ponderada das soluções a implementar, baseada nos parâmetros que considerem mais relevantes.

Por forma a estudar os impactos causados no comportamento térmico do edifício, uma construção de referência e diversas construções com diferentes geometrias, materiais e tecnologias foram desenvolvidas. A referência consiste num edifício de escritórios open-space em Utrecht, com uma área útil por andar de 1,600 m^2 e um pé-direito de 3 m, com um total de 6 andares de espaço útil e 21 m de altura. A área total útil é de 9,600 m^2, o que é considerado um edifício de grande dimensão no contexto holandês. Os conceitos de edifício estudados foram separados em diversas categorias, pretendendo-se assim estudar os impactos das medidas em isolamento: materiais, tecnologias de energias renováveis, estrutura e fatores externos. Adicionalmente, um caso de combinação foi construído com o intuito de avaliar a interação entre impactos. Na categoria de materiais, diferentes espessuras de isolamento e envidraçados com propriedades térmicas variáveis foram definidos; na categoria de energias renováveis, a produção de eletricidade através de pequenas turbinas eólicas e sistemas fotovoltaicos foi considerada; na categoria de estrutura, foram analisados edifícios com diversos rácios de janela-parede; na categoria de fatores externos, os efeitos de interação entre edifícios (sombreamento) e ainda as alterações climáticas foram avaliadas; no caso de combinação, foi realizada uma junção entre soluções de materiais e fatores externos. Ainda, para cada caso, foi desenvolvido um sub-método de dimensionamento dos equipamentos AVAC que garantiu uma escolha otimizada da tecnologia a implementar. O tipo e a combinação de equipamentos a instalar depende do perfil de fornecimento de energia ao sistema AVAC: sistema totalmente elétrico ou sistema a gás natural e eletricidade. Como suporte ao método geral, foi criado um inventário com as características técnicas e custos dos materiais, tecnologias de energias renováveis e dos equipamentos AVAC utilizados.

Entre outras conclusões, as principais considerações são apresentadas. Os casos da categoria materiais apresentaram poupanças de energia de até 35% para o isolamento e de até 20% para o envidraçado, com um impacto positivo para o ambiente. No entanto, nem todas as medidas foram efetivas em termos de custo. A implementação de sistemas de energias renováveis corresponde a uma medida sustentável que pode fornecer poupanças energéticas de até 30 MWh anuais, não obstante o benefício negativo (para um custo de energia não-residencial). Os diferentes casos de janela-parede rácio permitiram identificar mudanças drásticas no consumo elétrico para iluminação (entre +30% e -40% em relação à referência) e no investimento em equipamentos AVAC (podendo chegar até a +60%), sendo deste modo relevante a obtenção de um rácio otimizado que permita o menor investimento e consumo energético. Os efeitos externos estudados provaram exercer um impacto significativo na performance do edifício e recomenda-se que não sejam ignorados uma vez que o consumo energético AVAC registou uma subida generalizada de até 15%, podendo causar também a longo prazo um sub-dimensionamento do sistema que garante o conforto térmico dos ocupantes. Apesar de os resultados obtidos para cada conceito de edifício responderem à questão-base de investigação "What are the impacts of varying building concepts on the performance of buildings with respect to energy use, sustainability and cost?" para o edifício de referência em específico, estes resultados permitem também identificar tendências gerais que podem ser extrapoladas em termos de impacto de certas medidas na performance do edifício.

Os desenvolvimentos futuros incluem a expansão do programa de simulação, uma vez que a maior parte da análise económica foi realizada em outra ferramenta; a expansão e atualização do inventário, que inclua mais materiais e tecnologias e preços e caraterísticas atualizadas; a exploração de parâmetros adicionais de energia e sustentabilidade, dado que apenas uma pequena amostra de um vasto conjunto de indicadores foi utilizada; o estudo de materiais e tecnologias não-convencionais, como materiais de "mudança de fase", que tiram vantagem do perfil dinâmico da transferência de calor.

Palavras-Chave: edifícios, conceitos de edifício; performance térmica; conforto térmico; energia; sustentabilidade; sistema AVAC

Abstract

Energy consumption in the built environment represents approximately 40% of end-use energy consumption in the European Union. For office buildings with HVAC systems, the energy consumption of these systems corresponds up to a quarter of the total energy consumption registered in the building. Thus, several building concepts are developed with the aim of evaluating their impact on HVAC energy consumption and on the capacity of installations. These building concepts are constructed taking into account a specific building configuration consisting on a defined architectural structure, construction materials, installations that provide thermal comfort and other technologies that supply energy to the building. Additionally, external factors that influence building performance such as inter-building effects and climate change are analyzed. The outputs resulting from a dynamic thermal behavior analysis - performed in the building simulation tool IDA ICE - of the building concepts are translated into performance indicators of energy, sustainability and costs that allow users (or clients) to make a conscious decision based on the parameters that are most relevant to them.

The studied building concepts were separated into categories: materials, in which different thicknesses of insulation and glazing with varying thermal properties were defined; renewable energy technologies (RET), in which small wind turbines and PV systems that provide electricity to the building were considered; structure, in which buildings with different window-to-wall ratios (WWR) were analyzed; external factors, in which inter-building shading and climate change effects were assessed; and a combination case, in which a mix of material solutions with external factors was defined. The performance of each building concept was compared to a reference building. Furthermore, for each case, a sizing method for installations was developed in order to ensure an optimized selection of technologies. The type of implemented installations varies depending on the HVAC supply energy profile: all-electric HVAC system or natural gas and electricity HVAC system.

Among other important findings, some considerations are displayed. Material cases presented energy saving figures up to 35% for insulation and up to 20% for glazing, with an overall positive impact for the environment. However, not every measure was cost-effective. The implementation of RET systems corresponds to sustainable measures that can provide energy savings up to an annual figure of 30 MWh, even though with negative benefit (for non-residential cost of energy). External effects proved to have a significant impact on building performance, since HVAC energy consumption registered a generalized increase up to 15%.

Keywords: built environment; building concept; thermal performance; thermal comfort; energy; sustainability; HVAC system

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Abbreviations and Symbols

AC	Alternating Current
AHU	Air Handling Unit
CDD	Cooling degree days
COP	Coefficient of Performance (efficiency of heating)
DC	Direct Current
EER	Energy Efficiency Ratio (efficiency of cooling)
EPS	Expanded polystyrene
G_L	Most optimistic scenario of climate change
GHG	Greenhouse Gas
HDD	Heating degree days
IPCC	Intergovernmental Panel on Climate Change
KNMI	Royal Netherlands Meteorological Institute
NPV	Net Present Value
PF	Phenolic foam
PIR	Polyisocyanurate
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PUR	Polyurethane
PV	Photovoltaic
VAT	Value-added tax
W_H	Least optimistic scenario of climate change
WWR	Window-to-wall ratio
XPS	Extruded polystyrene

a_1	Loss coefficient (W/(m^2.K))
a_2	Loss coefficient (W/(m^2.K^2))
A_n	Area of the surface (m^2)
A_p	Area of the collector (m^2)
b'	Coefficient of roughness
B	Direct Benefit (€)
B_{an}	Annual cost of energy avoided (€)
c	Specific heat of the material (J/(kg.K))

C	Cost of energy (€/kWh)
C_0	Annual cash flow of the year 0 (€)
C_n	Annual cash flow of the year n (€)
C_p	Power coefficient (Betz limit)
dT/dt	Temperature difference at a given time (K)
E_{av}	Energy consumption avoided (kWh)
G	Irradiance (W/m^2)
G_c	Air conditioning load (W)
G_i	Internal heat gains (W)
G_s	Solar heat gains (W)
G_v	Ventilation heat gains (W)
h	Height difference (m)
i	Annual discount rate (%)
ΔI	Total investment (sum of ΔI_i and ΔI_m absolute values) (€)
ΔI_i	Difference between the investment on installations in the case study and the investment on installations in the reference case (€)
ΔI_m	Difference between the investment on the solution applied in the case study and the investment on the reference case solution (€)
n	Project lifetime (years)
P_u	Useful power (solar thermal collector) (W)
P_t	Power of a wind turbine (W)
P_w	Power of the wind (W)
PB	Payback time (years)
Q_L	Heat removed from the refrigerated space (J)
Q_H	Heat rejected to the warm space (J)
R_c	Thermal resistance ($m^2.K/W$)
RS_m	Module row spacing (m)
$RS_{min,m}$	Minimum module row spacing (m)
T_a	Air temperature (K)
T_f	Mean fluid temperature (K)
T_{int}	Internal room temperature (K)
T_{out}	External temperature (K)
u	Wind speed (m/s)
u_s	Meteorological wind speed at 10 m height (m/s)

u_z	Wind speed at height z (m/s)
U_n	Thermal transmittance (W/(m^2.K))
V	Volume of the material (m^3)
w_m	Module width (m)
$W_{net,in}$	Work done to carry out the heat transfer between spaces (J)

Greek symbols

α	Solar altitude (º)
α_L	Absorptivity
γ	Solar azimuth (º)
γ_c	Azimuth correction angle (º)
δ	Declination (º)
η_0	Optical efficiency (%)
η_c	Efficiency of the collector (%)
η_m	Mechanical efficiency of a turbine (%)
θ	Tilt angle (º)
ρ	Density of the material/air (kg/m^3)
ρ_L	Reflectivity
τ_L	Transmissivity
ϕ	Latitude (º)
ψ	Longitude (º)
ω	Hour angle (º)

Chapter 1 – Introduction

The current research project is framed within the building environment area of investigation. Further sub chapters present the social relevance of this topic and its scientific principles. Furthermore, the goal and scope of the study are defined and the main question and the research framework are formulated.

1.1. Societal background

Buildings account for 40% of end-use energy consumption in the European Union, being the largest energy consuming sector [1]. Given this reality, it is relevant to study possible ways to achieve energy savings and energy efficiency in the building sector, since a continuously increasing energy demand and associated emissions contribute to climate change. Billions of tons of greenhouse gases are emitted by buildings every year [2], thus contributing to progressively altering the climate of the planet.

In the developed world, buildings are of crucial importance in the lives of humans - we spend most of our time inside buildings. The characteristics of a building define its energy consumption. Furthermore, they also have a critical role on our productivity and well-being [3], through the comfort level, which depends on thermal, visual, and acoustic comfort, and air quality.

By constructing new buildings or renovating them with measures of high standards of energy performance, it is possible to show that both climate change mitigation and quality of life improvement can be achievable [4]. The purpose is to contribute and give solutions to a society that is increasingly aware of the need to adopt an efficient and sustainable way of living. Given this reality, buildings should follow a development in the way of net zero energy consumption with the integration of materials, technologies and unconventional energy sources that contribute to the reduction of their environmental impact and GHG emissions.

1.2. Scientific background

Building performance assessment is done by analyzing the thermal behavior of buildings in order to quantify the heat exchange with the environment. This way, the main losses/gains can be identified and attenuated with the aim of achieving thermal comfort.

In order to study thermal behavior of buildings, a number of aspects must be regarded. It is important to take into account the geometry of the building (wall surface, glazing surface, façade orientation, etc.), the construction materials, the occupation and use profile, temperature requirements for comfort, air quality (ventilation) and local weather conditions [5]. For this purpose, a dynamic energy balance should be with the aim of determining the energy demand. This energy balance is obtained by using a design tool in which a parametric model is developed. In this model, the input parameters of the aspects mentioned above translate into outputs that define performance indicators for energy use, cost and sustainability.

A dynamic approach is preferred for this study since the thermal inertia of the building fabric can influence to a considerable extent the energy demand. The higher the thermal inertia of a building the lower its cooling demand, since incoming solar radiation by day is stored in the walls and floors and then released by night when the building is not occupied anymore. This can have a larger impact in mild and warm climates. As an example of a case study [6] in a Mediterranean location, the cooling energy demand per unit of volume of a medium-heavy thermal inertia building fabric is around 4.3% less than a light building. The same comparison between light and medium-heavy thermal mass constructions, but with optimized conditions (presence of shading system and night cooling ventilation with an average cooling demand reduced by 50%), gives a difference of cooling energy consumption of 18.9%. Thus, the importance of taking into account thermal storage effects on energy consumption. Heating energy demand is however practically not affected in the example above when considering different thermal masses.

Another reason for applying a dynamic simulation on energy balance is to allow the study of the effect of implementing solutions such as phase change materials [7], of which the working principle is based on thermal storage.

A building solution is described as a specific building configuration consisting on a defined architectural structure, construction materials, installations that provide thermal comfort and other technologies that supply energy to the building. Different building solutions have of course different thermal balances, thus the preference of one building solution over another will have an impact in the performance of a building, which can be assessed with indicators of energy, sustainability and cost. Energy indicators evaluate energy consumption (and production) of a building, while sustainability indicators analyze the impact that a building has on the environment and cost indicators study profitability of measures of retrofitting or new projects' investment [8].

The external factors affecting long term performance of a building also play an important role in its thermal behaviour. These external factors are climate change and urbanization effects.

Climate change effects refer mainly to the trend of rising temperatures in the coming future. In cold climates heat demand is expected to decrease due to warmer winters, however a higher cooling demand in hotter summers may offset or exceed the savings in heating energy. In warm and hot climates cooling demand is expected to increase. In global terms, it is predicted that heating energy demand will decrease by 30% by 2100 while cooling energy demand will increase by 70% [9].

Urbanization effects refer to all the interactions between the building being studied and its surroundings. Urban design can cause considerable variations in the local environment, thus creating complex and dynamic microclimates. These urban microclimates and buildings are deeply connected: urban microclimates have impact on the building's energy consumption while buildings affect the microclimate. Therefore, buildings cannot be studied in isolation since the building's energy performance would not be accurately represented [10].

1.3. Goal and scope definition

The aim of the study is to analyze different building solutions and evaluate their impact on energy consumption, on the capacity of installations and on the cost of energy and installations. These outputs are translated into performance indicators of energy, sustainability and costs that allow users (or clients) to make a conscious decision based on the parameters that are most relevant to them.

1.3.1. Main research question

Taking into account previous considerations, a research question that portrays the aim of the research is elaborated:

What are the impacts of varying building concepts on the performance of buildings with respect to energy use, sustainability and cost?

The core of this research question lies on evaluating different building solutions mainly in terms of geometry, materials and technologies implemented and their impact on building performance (and installations capacity) that includes energy use, cost and sustainability. Additionally, external factors that influence the building's thermal behavior such as inter-building effects and climate change are analyzed.

In order to answer this question, it is intended to make use of an existing building energy performance simulation program that allows to simulate a reference building and several other building concepts. The program should also allow to be extended with additional modules in order to incorporate new technologies available in the market. Additionally, the tool chosen is intended to be user friendly, with an appealing visual and self-explanatory graphical interface that enables the user to quickly observe the performance result of different solutions.

1.3.2. Sub questions

A few sub questions are defined with the intention of structuring the project and finding an answer to the main research question:

• Which are the most representative indicators of energy, sustainability and economics?

• Which is the most effective way to quantify and present the outcomes so the users can make an informed decision based on the factors that are most important to them?

• Which building concepts are most relevant?

• How to measure long term external factors that impact the thermal behavior of a building?

In the next sections, the fundamental concepts behind the thesis research are defined and described, the method is presented in a detailed way and in a step-by-step sequence, the results are displayed, a discussion of the results is performed and finally conclusions and future developments are drawn.

Chapter 2 – Theory

In this chapter, the theories and concepts employed throughout the study are described. The applied approach to assess building energy performance corresponds to the dynamic heat transfer theory while the assumption used to assess occupants' comfort corresponds to the Fanger's theory of thermal comfort. Additionally, several concepts and theories regarding solar geometry and radiation, building solutions (materials, installations and renewable energy sources), performance indicators to evaluate energy, sustainability and cost of these solutions and external factors affecting long term performance of buildings (climate change and inter-building effects) are explained.

2.1. Dynamic Heat Transfer

To account for heat transfer between the building and the environment the first law of thermodynamics of energy conservation is applied. The energy conservation inside each zone or room of the building can be represented by [11]:

$$G_i + G_s + G_v + G_c = \rho V c \frac{dT}{dt} + \sum_{n=1}^{k} A_n U_n (T_{int} - T_{out}) \; [W] \qquad (1)$$

Where G_i are internal heat gains, G_s solar heat gains, G_v ventilation gains, G_c are acclimatization gains (the variable of interest) and U is the thermal transmittance of the room surfaces. The heat balance described by equation 1 includes energy transfer through conduction, convection (ventilation gains) and radiation (solar gains) mechanisms as well as energy transfer through lighting, equipment and occupants (defined as internal heat gains) and air conditioning load. The transient term of the equation represents the thermal inertia of the building envelope. Figure 1 depicts the energy transfer processes present in a room.

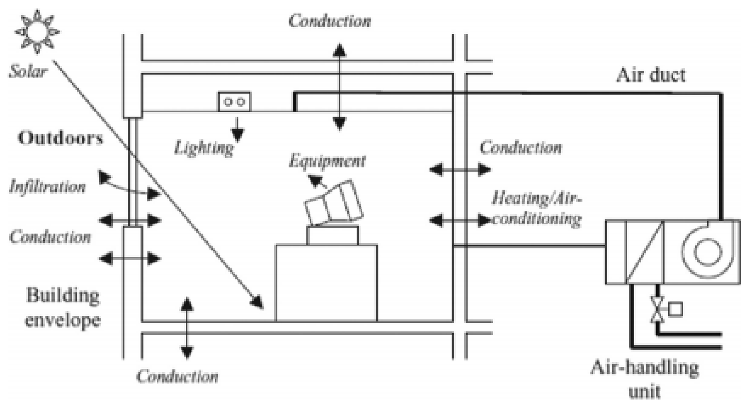

Figure 1 - Energy transfer processes occurring within a building space. Source: [12]

2.2. Solar Geometry

Solar geometry concepts are used to study the sun path at a set location and its variations according to the hours of the day and the days of the year. The first step for this characterization is to obtain the latitude and longitude of the location, which allow to determine the solar altitude and azimuth at any fixed day and hour. These data are fundamental to design the building geometry and the window-to-wall ratio (WWR) and to a correct implementation of solutions such as shading devices and solar-based renewable energy technologies.

2.2.1. Latitude and Longitude

Any point on the earth's surface can be located through the astronomical coordinates system – latitude (ϕ) and longitude (ψ). The latitude is defined based on the equatorial plane and is measured by an angle ranging from 0º to 90º (positive for points north of the equator and negative for points south of the equator). The longitude is defined positive eastwards from Greenwich (England) and is measured by an angle ranging from 0º to 180º (positive or negative) [13].

2.2.2. Altitude and Azimuth

The sun's position at a given time of the day in a particular location is represented through its altitude and azimuth. These coordinates vary throughout the day due to earth's rotation and throughout the year due to earth's orbit around the sun. The altitude corresponds to the angle measured, in a vertical plane, between the horizontal and the direction of the sun (between 0º and 90º). The azimuth corresponds to the angle measured, in a horizontal plane, between the North and the direction of the sun projected on the horizontal plane. For the northern hemisphere, the azimuth is 0° for the south, -90° for the east and +90° for the west [14].

The solar altitude can be determined from the following equation:

$$\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \ [°] \tag{2}$$

where δ corresponds to the solar declination (angle between the equatorial plane and the plane of earth's revolution) and ω corresponds to the hour angle (angle through which the earth has rotated since solar noon).

The solar azimuth can be obtained from the following expression:

$$\cos\gamma = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi} \ [°] \tag{3}$$

2.3. Solar Radiation

Solar radiation is the main source of energy of the planet, providing heat and natural light. It is defined by the amount of radiant energy emitted by the sun that reaches a fixed surface and can be divided in two components: direct and diffuse radiation. In this section, relevant concepts for this research project related to solar radiation are introduced: properties of light (reflection, absorption and transmission), solar factor (g-value) and illuminance.

2.3.1. Reflection, Absorption and Transmission

When the solar radiation reaches the glazing surface of a building, three phenomena of heat exchange can occur: reflection, absorption and transmission [11].

Reflection corresponds to the change of the incident radiation direction after reaching the glazed surface. Transmission occurs when radiation passes through the glass. Absorption takes place when radiation interacts with the glass, causing an increase of its internal thermal energy.

Reflectivity (ρ_L) is defined as the fraction of the irradiation that is reflected, absorptivity (α_L) as the fraction of the irradiation that is absorbed, and transmissivity (τ_L) as the fraction of the irradiation that is transmitted. Since all the irradiation must be reflected, absorbed, or transmitted, the following expression reflects the conservation of energy for the incident solar radiation in a glazed surface:

$$\rho_L + \alpha_L + \tau_L = 1 \tag{4}$$

2.3.2. Solar factor (g-value)

The solar factor (g-value) measures the percentage of heat that passes through a glass. This heat consists on the fraction of solar heat that is transmitted through the glazing in addition to the fraction of solar heat that is emitted from the glass to the internal environment. The lower the solar factor the higher the solar protection and therefore the higher the performance of the glass. Figure 2 illustrates the light phenomena occurring in a glass and depicts the definition of the g-value (overall gain).

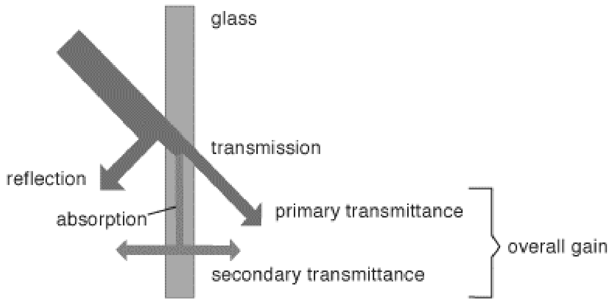

Figure 2 - g-value (overall gain) of a glazed surface. Source: [15].

2.3.3. Illuminance

The basic unit of light is the lumen (lm). It is used to describe the total flow of light from a source, and can also be called luminous flux. Another light concept is the luminous efficacy, that defines the relationship between a lamp’s light output and its electrical input (lm/W). As an example, an incandescent lamp has a low efficacy because most of its power is radiated in the form of heat and not as light. Illuminance, measured in lux (lx), corresponds to the density of the luminous flux, this is, the amount of light falling on a surface. Thus, lux is equivalent to lumen per square meter [16].

All these concepts about the visual properties of light are used to determine the required illuminance on the working plane. Part of this illuminance is provided by natural lighting while the other part is provided by artificial lighting (lamps). By obtaining the natural illuminance in the working plane at a given time, it is possible to determine the required number of lamps to install in order to provide the adequate visual conditions.

2.4. Thermal Comfort

Thermal comfort assumes a central role in the study, since occupants’ comfort must be guaranteed whatever the building solution considered. In order to assess thermal comfort, Fanger’s theory is used. This theory is based on the assumption that thermal equilibrium is reached whenever the internal heat generated by the organism is exchanged with the environment at the same rate, thus keeping internal body temperature constant. In order to assure thermal comfort, it is also crucial to avoid local discomfort conditions such as high ventilation speed, radiative asymmetry and high vertical temperature gradient. Fanger’s model based in thermal equilibrium is named Predicted Mean Vote (PMV). This model combines four physical variables (air temperature, air speed, radiant average temperature and relative humidity) and two personal variables (clothing, metabolic activity). The thermal sensation index ranks from +3 (“too hot”) to -3 (“too cold”), being 0 the vote corresponding to comfort [17]. Table 1 illustrates the complete scale of the PMV.

Table 1 - Fanger's thermal sensation scale (PMV). Source: [16]

Predicted Mean Vote	
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Another indicator proposed by Fanger is the Predicted Percentage of Dissatisfied (PPD), which estimates the fraction of dissatisfied people that feel hot (+3, +2) or cold (-2, -3). Figure 3 depicts the dependence of PPD on PMV.

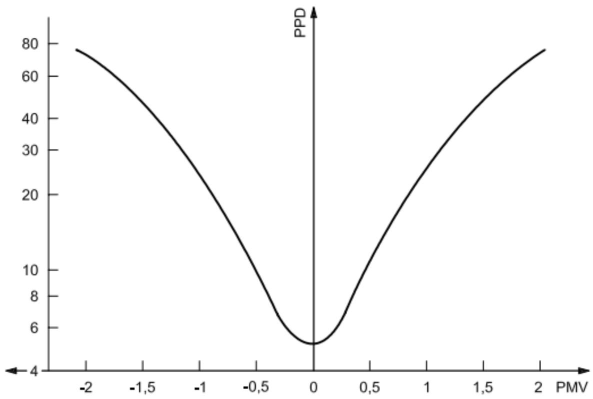

Figure 3 – Relation between the Predicted Percentage Dissatisfied and the Predicted Mean Vote. Source: [17]

The international regulation EN ISO 7730 uses Fanger's studies defining categories of thermal comfort. Minimum recommended condition for indoor environment is classified as Category II, defined by PPD < 10 % (or a thermal sensation index of |PMV| < 0,5).

2.5. Building solutions

Several building solutions are considered in this research in order to provide a broad overview of effects regarding the building thermal behavior. In the present section, a short description of the materials, installations and renewable energy technologies is presented.

2.5.1. Materials

As described further in the method section, the only materials of the building envelope subject to change are insulation and glazing.

2.5.1.1. Insulation

The insulation layer is the layer that mainly contributes to the overall thermal behavior of the building envelope. Therefore, it is relevant to study the reduction of heat loss through the walls, floor and roof to the external environment by applying insulation.

Insulation materials can be characterized by its thermal, acoustic and environmental (life cycle assessment) properties [18]. For the purpose of this research however, the focus is centered on its thermal properties, including: thickness (m), thermal conductivity (W/(m.K)), density (kg/m^3) and specific heat (J/(kg.K)). For economic evaluation purposes, parameters such as lifetime (years) [19] and price per square meter (€/m^2) are also needed. Furthermore, the type of application must be known: wall, roof, sloped roof or floor. The most common types of insulation materials include stone wool, glass wool, expanded polystyrene (EPS), extruded polystyrene (XPS), phenolic foam (PF), polyurethane (PUR), polyisocyanurate (PIR) and wood fibers.

2.5.1.2. Glazing

The glazed envelope of a building plays a crucial role in terms of energy transfer but also on daylight admittance [20]. The solar radiation entering through the glazing causes undesired solar gains in summer but has a positive effect on winter. Additionally, in terms of heat transfer through conduction, glazed surfaces have generally a higher U-value than the rest of the building envelope, thus an important source of heat loss. Glazing, as mentioned before, represents a source of daylight admission which is a fundamental factor for the occupants' comfort and also determines the energy used for artificial lighting.

For this type of materials, the relevant characteristics used to evaluate its energy performance correspond to U-value (W/(m^2.K)), g-value, solar transmittance (%), external reflection (%) and external and internal emission (%). For economic considerations, the lifetime (years) and the price per unit of surface is required (€/m^2).

2.5.2. Installations

Several types of installations can be applied with the aim of guaranteeing the thermal comfort of the occupants in a room. In this section, some of the most common technologies are described: chillers and heat pumps, air conditioners, boilers, water radiators and air handling units (AHU). Pipe connections between installations are not considered for energy losses or cost.

2.5.2.1. Chillers/Heat pumps

Heat flows naturally in the direction of decreasing temperature, i.e., from high temperature regions to low temperature ones. However, the transfer of heat from a low temperature region to a high temperature one requires work performed by devices called refrigerators or heat pumps [21]. Chillers and heat pumps consist on the same operating process, differing only in their objectives. The goal of a chiller is to keep the refrigerated space at a low temperature by removing heat from it while the goal of a heat pump is to maintain a heated space at a high temperature by absorbing heat from a low temperature source (normally water or air) and supplying it to a warmer internal environment.

Chillers and heat pumps are technically defined by heating and/or cooling capacity (kW) and COP and/or EER (efficiency of the system). The efficiencies of these technologies are given by the following equations:

$$COP = \frac{Desired\ output}{Required\ input} = \frac{Heating\ effect}{Work\ input} = \frac{Q_H}{W_{net,in}} \tag{5}$$

$$EER = \frac{Desired\ output}{Required\ input} = \frac{Cooling\ effect}{Work\ input} = \frac{Q_L}{W_{net,in}} \tag{6}$$

For cost analysis purposes, lifetime (years) and price (€) data must be collected.

2.5.2.2. Air conditioners

An air conditioner is a device designed to maintain the indoor air temperature at a constant value. The single-split type is the most common type used in Europe [22]. It consists in two separate units: an indoor unit and an outdoor unit, connected by a pipe where the refrigerant flows. The indoor unit is composed by an evaporator and a fan, while the outdoor unit is composed by a condenser and a compressor. Generally, these systems are designed as reversible operating, thus functioning like a heat pump.

Air conditioning units are technically defined by heating and/or cooling capacity (kW) and COP and/or EER (efficiency of the system). For cost analysis purposes, lifetime (years) and price (€) data must be collected.

2.5.2.3. Boilers and water radiators

A boiler is a device that transfers energy from the combustion of a fuel into the circulation water in order to produce hot water. The hot water is then transported through a piping system which distributes the water to radiators with the purpose of heating the internal environment. Boilers can also be used to provide hot water for the occupants. They are characterized in terms of energy by its efficiency (%) and heating capacity (kW). Water radiators used for zone heating are defined in terms of energy by its heating capacity (kW). The lifetime (years) and price (€) of these installations are essential information that is necessary to perform cost calculations.

2.5.2.4. Air Handling Units

An Air Handling Unit (AHU) is a central air conditioner station that controls the air introduced into the building by the ventilation ductwork. The function of the AHU is to introduce outdoor air needed to ventilate the internal environment. However, the air needs to be previously treated before being introduced in the room in order to comply with indoor air quality requirements. Thus, the AHU heats/cools and humidify/dehumidify the incoming air. The main characteristic to take into consideration when choosing an AHU for ventilation purposes is to determine the needed air flow (m^3/h).

2.5.3. Renewable Energy Technologies

Renewable energy technologies are used as sustainable solutions that improve the environmental performance of a building, turning it more self-sufficient in terms of energy consumption. By producing electricity, these technologies effectively avoid energy that is mainly derived from fossil fuels. Additionally, they have zero carbon emissions, thus having a big potential for CO_2 emissions savings. The addressed technologies for this study are small wind turbines and photovoltaic systems.

2.5.3.1. Wind turbines

Wind turbines are devices that convert the kinetic energy present in the wind to mechanical energy and eventually into electricity. The wind power incident in a surface A is given by:

$$P_w = \frac{1}{2} A \rho u^3 \ [W] \tag{7}$$

Where ρ is the density of air (kg/m^3) and u^3 is the air speed. By observing the previous equation, it is evident that the power of the wind depends on its speed (to the cube). The power that a turbine can extract from the wind is however lower:

$$P_t = \eta_m C_p \ \frac{1}{2} A \rho u^3 \ [W] \tag{8}$$

In ideal conditions, the theoretical maximum of C_p is 16/27=0.593 (known as the Betz limit), i.e., a wind turbine can theoretically extract a maximum of 59.3% of the airflow energy content [13]. Under real conditions, the efficiency tends to be lower than 50% due to losses ($\eta_m C_p$) and the power does not increase with the cube of the wind speed at higher speeds. The power extraction of a wind turbine can be characterized by its power curve, illustrated in Figure 4.

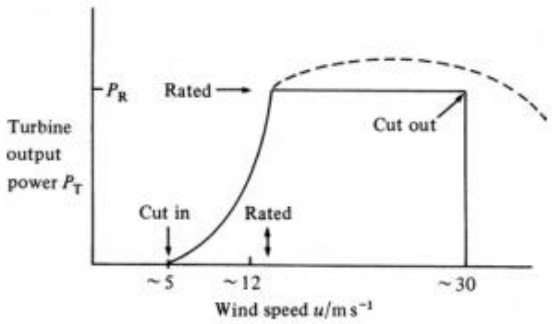

Figure 4 - Wind turbine operating regions and power performance. Source: [13]

The power produced by the wind turbine increases from zero, below the cut-in wind speed (approximately 5 m/s) to the maximum at the rated wind speed. Above the rated wind speed, the wind turbine continuously produces the same rated power but at a lower efficiency, until shut down is initiated as soon as the wind speed becomes too high.

Another aspect to take into consideration is that wind speed varies considerably with height above ground. A turbine with a hub height of e.g. 30 m will experience much stronger winds than a person at the ground level. This effect can be measured by using an approximate expression that determines the wind speed u_z at a height z:

$$u_z = u_s \left(\frac{z}{10\,m}\right)^{b\prime} [m/s] \tag{9}$$

Where u_s is the air speed at 10 m height. The coefficient b' depends on the profile of the location (urban, suburban, countryside, etc) and shapes the wind speed curve depicted in Figure 5:

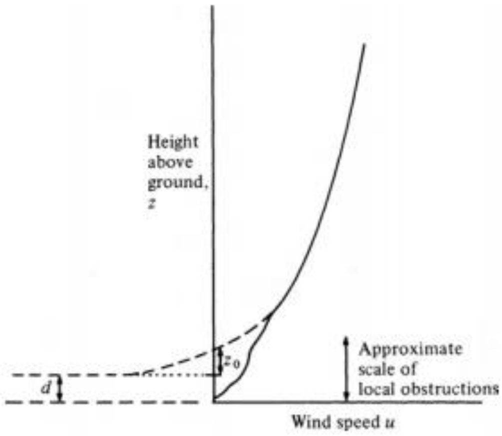

Figure 5 - Wind speed variation with height. Source: [13].

Considering that there is no available land where turbines can be installed, the turbines are to be applied in the rooftop. For these kind of applications, small scale wind turbines are the most adequate. These turbines have a rotor diameter ranging from 3 m to 10 m and a power capacity of between 1.4 kW and 20 kW and they can be classified as vertical axis or horizontal axis wind turbines [23].

In order to obtain the number of turbines to install and to perform an energy analysis, the parameters needed are: diameter of the rotor (m), hub height (m), rated power (kW) and power curve of the turbine. For additional cost calculations, the lifetime (years) and the investment (€) must be acquired from the manufacturer.

2.5.3.2. Photovoltaic systems

Photovoltaic (PV) systems are used to convert sunlight into electricity. The main component of any photovoltaic system is the PV module, which is composed of several interconnected solar cells. PV modules are connected together into panels (connection in series) and arrays (connection in parallel) with the aim of meeting a defined energy need. The solar array is connected to an inverter which converts the direct current (DC) generated by the array into alternating current (AC), thus being compatible with the electricity from the grid. The AC output from the inverter is connected to the home's electrical panel in the net metering type of configuration [24]. The decision to use this type of configuration is based in the national law of the chosen location [25]. In this structure, the utility charges for the net consumption of electricity. Figure 6 represents a PV system with a net metering configuration.

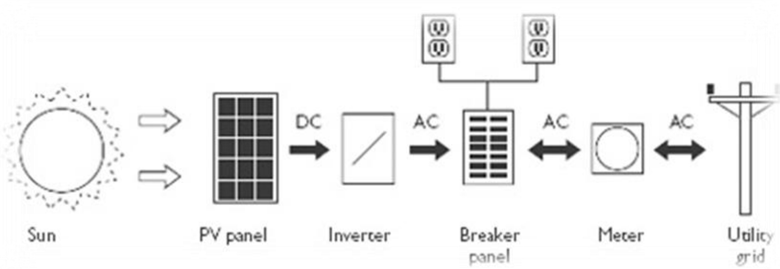

Figure 6 - Net-metering PV system configuration. Source: [24]

For energy and sustainability related characterizations, rated power (W), efficiency (%) and area (m^2) of the type of module used in the system must be known. The efficiency of the inverter is also needed. For cost related analysis, the useful data to be gathered are price (€) and lifetime (years) of the module.

2.6. Performance Indicators

The performance of each building solution will be evaluated in terms of energy, sustainability and costs. The following paragraphs present the performance indicators chosen in each category, a non-extensive list of the broad range of indicators that can be applied in these type of studies [8].

Energy is described by measuring heating and cooling load (MWh), capacity or power of installations (MW), energy consumption by type of fuel for both heating and cooling demand (MWh), energy consumption for lighting and equipment (MWh), energy production (when applicable) (MWh), primary energy demand (MWh) and renewable primary energy (when applicable) (MWh).

For the assessment of sustainability of building renovation projects or new buildings, the chosen indicators are CO_2 emissions (ton CO_2), amount of renewable energy (MWh) and primary energy (MWh). Thus, it is evident that the environmental impact is closely related to energy.

Finally, economics should be a focus in order to evaluate if the solutions that are intended to implement are viable in terms of costs. These costs are measured in the form of capital investment (€), cost of energy (€), direct benefit (€), payback time (years) and net present value (€).

2.7. External Factors affecting building performance

There are external factors to the building envelope that affects its performance. The aim of studying these elements is to determine if they are essential to a correct assessment of the building thermal behavior. In other words, may the omission of these factors induce a relevant deviation error in the results? One of the factors is climate change, which could affect significantly the building performance in the long run. The other is the effect that the shading induced from surrounding buildings has on the building operation.

2.7.1. Climate Change

Measurements of gas present in polar ice show that the concentration of GHG's in the atmosphere has increased steeply since the Industrial Revolution in the 18th century. Recent data from direct measurements of atmospheric air also corroborates the increased concentration of these gases. For instance, the global average concentration of CO_2 in the atmosphere increased from 280 ppm in 1800 to 380 ppm in 2005.

The IPCC authoritative review (2007) [26] estimates that the increase of GHG concentrations between 1750 and 2000 caused radiative forcing of 2.5 W/m^2. Positive radiating forcing causes an increase of temperature in the globe's surface, also known as global warming. The rate of increase of the global mean surface temperature has itself increased over recent decades due to higher global fossil fuel consumption.

Authoritative studies predict that if fossil fuel combustion continues at current or even higher rates, climate change will become much more severe by 2050 and beyond, causing severe damages to the environment and to the society.

2.7.2. Inter-building effects

Urbanization is defined as the migration of rural inhabitants toward towns and cities for the promise of a better life. This phenomenon is creating profound effects in the urban environment (quality of urban air, urban temperature, energy consumption and water supply, pollution and waste products, etc) and is expected to aggravate in the near future [10]. Urban built environments are evolving in the direction of much tighter spatial interrelationships, which could increase urban energy consumption, and also influence the surrounding microenvironment and microclimate. Inter-building effects include mutual shading and mutual reflection between buildings.

Chapter 3 – Method

In this chapter, the method applied to answer the research question is described. To find an answer for this question, a reference case is defined and several case studies are developed, each one addressing a different building solution or concept. Only by doing this it is possible to quantify the effect that building solutions (and external factors) have on the long term building's thermal behavior. Figure 7 illustrates the method used. First of all, building concepts are defined. This is done by applying different materials and technologies taken from a self-created inventory and by defining the building location and geometry. Then, the inputs required are given to the simulation program and the simulation is performed. The program gives hourly outputs (or any other defined time step) that need to be translated into performance indicators of interest that allow to characterize the building concepts. This output-indicators translation is done after selecting and sizing the installations that provide heating, cooling and ventilation to the building.

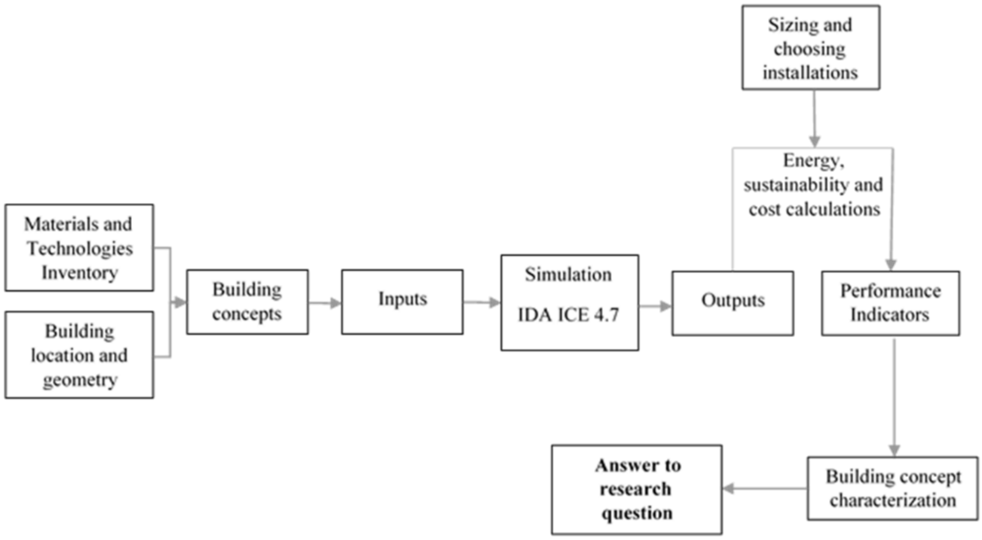

Figure 7 - General method of the research project

3.1. Simulation Software

The requirements of the thermal behavior of buildings have become increasingly strict over the years by EU regulations [27] and country specific regulations. Thus, nowadays designers need tools that are capable of answering very specific questions in a short amount of time. Through the use of energy simulation software, designers can consider specific solutions for heating, cooling, ventilation, lighting, etc. The main advantage of using these simulation tools is that they allow to study the thermal behavior of buildings prior to their construction or to simulate the performance in existent buildings in their current conditions, thus establishing the best retrofitting measures to adopt. Most of the research method is thus performed by using a building simulation software.

The simulation program was chosen according to fundamental criteria that the company supporting the research intended to see incorporated: a program that allows to flexibly simulate buildings equipped with different building solutions in terms of materials, geometry and technologies; a program that allows, for further investigations, to add modules in order to incorporate new technologies available in the market; a tool that is user friendly, with an appealing visual interface that enables the user to quickly observe the performance results of different solutions.

The proposed tools were ESP-r and IDA ICE, both including dynamic thermal heat transfer. The tool that best represented the intended criteria was IDA ICE. The main advantages of this software include: possible extensions to the initial model; the mathematical model can be observed to inspect variables, parameters and equations; the research models can be easily performed [28]. The most recent version of IDA ICE (4.7) was used for the simulations.

3.2. Materials and Technologies Inventory

A non-extensive inventory of materials, installations and renewable energy technologies that include their technical and financial characteristics (described in section 2.5) was created to support the calculation of the performance indicators for energy, sustainability and cost.

The materials incorporated in the database correspond to insulation and windows, which are the components that have the most significant impact on the energy performance of the building envelope. The other elements of the façade are considered to remain constant throughout the project, thus not making part of the costs calculations. The installations included in the database correspond to all the equipment necessary for heating and cooling the indoor environment and for treatment of supply and return air (temperature, humidity) in the air handling unit. The AHU investment was not included since it is the same for all the case study scenarios. The inventory incorporates renewable energy technologies such as PV systems and small wind turbines which supply energy to the building.

The gathering of data was done by directly contacting companies which were suggested by Witteveen+Bos, the company that supports the research. Most of the data were collected from regional manufacturers in the Netherlands where the building is located, but information from some items was collected from manufacturers in Portugal due to the lack of available data. Since the products originate from two different countries, an empirical observation of comparable items from the same multinational company was made in order to assure that prices do not differ significantly. Given this, all the prices were collected before taxes, and then the tax of the Netherlands was added (21% VAT).

3.3. Building location and geometry

A typical open space office building located in Utrecht, the Netherlands is taken as the reference. More specifically, the building is located in De Bilt, 5 km away from the center of Utrecht, where a meteorological station is located. The exact coordinates are 52.1ºN (latitude) and 5.2ºE (longitude), 4 meters above sea level.

The office building used for the project has a simple rectangular structure of 62.5 meters long and 25.6 meters wide - ground area of 1,600 m^2 per floor. The building has 6 floors with regular occupancy and an attic - total floor area 9,600 m^2. This total available area lays in a category considered big-sized for office buildings, which represented 10% of the demand for office space in the Netherlands in 2015 [29].

Each floor has 3 m height, thus a total height of 21 meters from roof to ground. The glazing area in each different orientation is determined by taking into account the concept of optimal window-to-wall ratio (WWR), which is obtained by minimizing, on a yearly basis, the total amount of energy used for heating, cooling and lighting. A study made to search for the optimal WWR in office buildings in different European climates determined that, for Frankfurt, these values are 40% for the south façade, 43% for the north façade, 41% for the west façade and 39% for the east façade [30]. These are the WWR taken for an office building in the Netherlands, since Frankfurt is the closest location and has a similar weather. This means that for this project the optimal window area for the south façade is 75.0 m^2, for the north façade is 80.6 m^2, for the west façade is 31.5 m^2 and for the east façade is 30.0 m^2 per floor.

The geometry of the building and its orientation are presented in Figure 8.

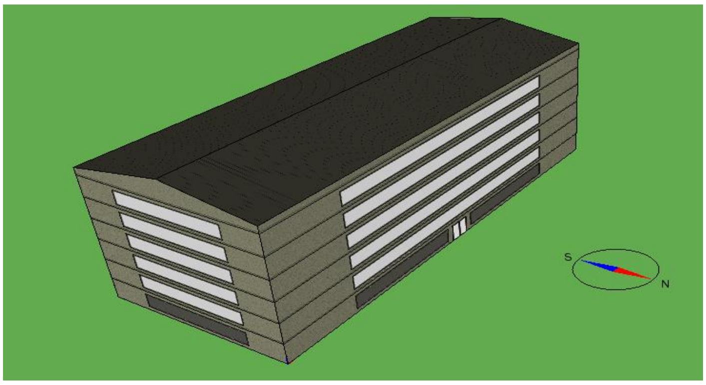

Figure 8 - Geometry and orientation of the studied building in IDA ICE

3.4. Cases definition

First of all, a reference case is developed. All the case studies are compared with the reference. The case studies correspond to the adoption of one building concept at a time, and they are divided in the following categories:

- Materials: include building concepts with different level of insulation and different types of glazing, giving a total of 5 cases.
- Renewable energy technologies: include PV system and small wind turbines, giving a total of 2 cases.
- Structural changes: include different WWR, giving a total of 2 cases.
- External factors: include inter-building effects and different scenarios of climate change, giving a total of 3 cases.

Then, based on the results of these simulations, a case study in which a combination of these solutions/factors are analyzed. The case is made with the most profitable level of insulation and type of glazing in combination with the most realistic scenarios of external factors.

3.4.1. Reference Case

In terms of the building envelope, typical constructions for walls, floors and roofs were applied using IDA ICE database. The only material of these constructions that is subject to change in further case scenarios is the insulation, thus a reference level of insulation is defined. Furthermore, glazing is subject to change in some of the cases, so a reference glass type is also needed. In the reference, minimum values of insulation available in the inventory are considered for each element of the façade. For windows, the highest U-value glazing is chosen from the inventory.

- **External walls:** 20 cm concrete, 2 cm insulation, 10 cm brick (inside to outside). Total thickness 32 cm, U-value 0.71 W/(m^2.K).
- **Internal walls:** not defined. Considered an open space building office (effect of pillars are not considered since they cannot be included in the 3D model of the building).
- **Internal floors:** floor coating 1 cm, lightweight concrete 2 cm, concrete 15 cm (downwards). Total thickness 18 cm, U-value 2.23 W/(m^2.K). No insulation for internal divisions, except for division between sixth floor and the attic. In this case, an additional layer of 2 cm is considered: total thickness 20 cm, U-value 0.71 W/(m^2.K).
- **Roof:** 4 cm insulation, 18 cm concrete (inside to outside). Total thickness 22 cm, U-value 0.46 W/(m^2.K).
- **External floor:** floor coating 1 cm, insulation 3 cm, concrete 25 cm (inside to outside). Total thickness 29 cm, U-value 0.60 W/(m^2.K).

- **Glazing:** Double glazing. 4 mm glass, air space 14 mm, 6 mm glass (inside to outside). U-value 1.50 W/(m^2.K); g-value 0.51; solar transmittance 0.45; internal emissivity 0.06; external emissivity 0.11; external reflectance 0.38.
- **Doors:** wood 6 cm. As this element is going to remain constant through all the simulation, thickness was chosen in order to have approximately the maximum average U-value of 1.65 W/(m^2.K), this way complying with requirements of retrofitted and new buildings (explained further in the text).
- **Thermal bridges:** considered to have typical values, which the program calculates automatically. A sample of the thermal bridges magnitude for different types of constructions is shown in Figure 9.

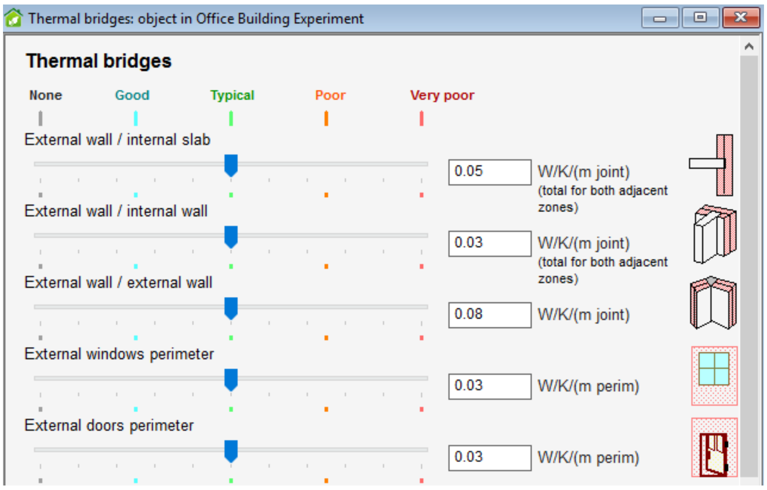

Figure 9 - Sample of thermal bridges magnitude per type of construction

3.4.2. Materials Cases

This section describes the definition of building solutions that represent different levels of insulation and different types of glazing. The cases are studied one by one in order to quantify their isolated effect. Within each category it is possible to observe what would be the best option in terms of energy, sustainability and cost.

3.4.2.1. Insulation

In order to build these cases, we recur to the Dutch law [31]. The minimum values of resistance (R_c) or maximum U-values of walls, floors, roofs, windows and doors are taken into consideration.

For new buildings, external walls and internal partitions that make contact with non-heated spaces must have a minimum resistance of R_c = 4.50 m^2.K/W (U = 0.22 W/(m^2.K)) , floors in contact with soil or water a minimum R_c = 3.50 m^2.K/W (U = 0.29 W/(m^2.K)) and external floors or roofs a minimum of R_c = 6.00 m^2.K/W (U = 0.17 W/(m^2.K)).

In retrofitted buildings where insulation layers are replaced, the minimum resistances are R_c = 2.50 / 1.30 / 2.00 m^2.K/W (U = 0.40/0.77/0.50 W/(m^2.K)) for floors, walls and roofs respectively. Windows, doors and frames must have individually a maximum U-value of U=2.20 W/(m^2.K) and an average of U= 1.65 W/(m^2.K) for the whole building for both retrofitted and new buildings.

Simulation of different thicknesses of insulation is done for three cases: minimum requirements for retrofitted buildings, minimum requirements for new buildings and finally highest thickness available according to the inventory of insulation materials.

<u>Case I.1:</u> Retrofitted Building

- **External walls:** 6 cm insulation, U = 0.29 W/(m^2.K). As the minimum insulation for retrofitted buildings was already complied in the reference case (U ≤ 0.77 W/(m^2.K)), a step of 4 cm was applied.
- **Internal floor (between sixth floor and attic):** 6 cm insulation, U = 0.29 W/(m^2.K). Corresponds to the minimum insulation required to comply with retrofitted legislation (U ≤ 0.40 W/(m^2.K)).
- **Roof:** 8 cm insulation, U = 0.23 W/(m^2.K). As the minimum insulation for retrofitted buildings was already complied in the reference case (U ≤ 0.50 W/(m^2.K)), a step of 4 cm was applied.
- **External floor:** 5cm insulation, U = 0.39 W/(m^2.K). Corresponds to the minimum insulation required to comply with retrofitted legislation (U ≤ 0.40 W/(m^2.K))

<u>Case I.2:</u> New Building

- **External walls:** 8 cm insulation, U = 0.22 W/(m^2.K). Corresponds to the minimum insulation required to comply with new buildings legislation (U ≤ 0.22 W/(m^2.K))
- **Internal floor (between sixth floor and attic):** 8 cm insulation, U = 0.22 W/(m^2.K). Corresponds to the minimum insulation required to comply with new buildings legislation (U ≤ 0.22 W/(m^2.K))
- **Roof:** 12 cm insulation, U = 0.16 W/(m^2.K). Corresponds to the minimum insulation required to comply with new buildings legislation (U ≤ 0.17 W/(m^2.K))
- **External floor:** 8 cm insulation, U = 0.26 W/(m^2.K). Corresponds to the minimum insulation required to comply with new buildings legislation (U ≤ 0.29 W/(m^2.K))

<u>Case I.3:</u> Best available

- **External walls:** 12 cm insulation, U = 0.15 W/(m^2.K)
- **Internal floor (between sixth floor and attic):** 16 cm insulation, U = 0.12 W/(m^2.K)
- **Roof:** 12 cm insulation, U = 0.16 W/(m^2.K)
- **External floor:** 10 cm insulation, U = 0.21 W/(m^2.K)

3.4.2.2. Glazing

Impact of glazing in building performance is measured in this type of scenarios. The frame of the windows is always the same as in the reference case, which is considered to represent 10% of it and to have an U-value of 2.00 W/(m^2.K). The Dutch requirements are for an individual window U ≤ 2.20 W/(m^2.K) and for the whole glazing of the building $\overline{\text{U}} \leq$ 1.65 W/(m^2.K). As the glazing and frame properties are identical for every window, each window needs to have a heat transfer coefficient of U ≤ 1.65 W/(m^2.K) in order to comply with the average value. In the reference case, Dutch law requirements are already in accordance, thus a glazing U-value step of 0.4 W/(m^2.K) is done. Given this, two cases are considered: glazing with a U-value of 1.1 W/(m^2.K) and glazing with 0.7 W/(m^2.K). Other properties such as g-value and solar transmittance are substantially similar between cases. This means that the main effect to be studied corresponds to heat transfer through windows and not solar gains, due to the lack of an extensive glazing inventory.

<u>Case G.1:</u>

- **Glazing:** Double glazing. 4 mm glass, argon space 14 mm, 6 mm glass (inside to outside). U-value 1.10 W/(m^2.K); g-value 0.51; solar transmittance 0.45; internal emissivity 0.06; external emissivity 0.11; external reflectance 0.38.

<u>Case G.2:</u>

- **Glazing:** Triple glazing. 4 mm glass, argon space 12 mm, 4 mm glass, argon space 12 mm, 6 mm glass (inside to outside). U-value 0.70 W/(m^2.K); g-value 0.53; solar transmittance 0.47; internal emissivity 0.05; external emissivity 0.14; external reflectance 0.31.

3.4.3. Renewable Energy Technologies Cases

These scenarios account for renewable energy technologies used to provide a share of the energy demand of the building. Net-metering configuration PV systems and small wind turbines are studied to supply part of electricity consumption. In the next subsections, the sizing of the renewable energy systems is described.

3.4.3.1. Small wind turbines

The small wind turbines to be implemented are taken from the inventory and presented in Table 2.

Table 2 - Small wind turbines properties. Source: [32]

Small wind turbines						
Model	**Diameter (m)**	**Rated Power (kW)**	**Height Tower (m)**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
Passaat	3.1	1.4	12	9,646	25	Fortis Wind Energy
Montana	5.0	5.8	12	18,013		
Alizé	6.3	10.0	12	43,111		

It is considered that the turbines are to be installed on the rooftop, so the number of turbines is limited by the area available of approximately 1620 m^2. The height wind turbine nacelle is approximately 32 m, considering 20 m height of the rooftop and an additional 12 m height of the tower. Supposing a space between turbines of 5D x 5D, with D being the diameter of the blades, it is possible to determine the number of turbines of each type that can be mounted and the share of the yearly electricity demand that is covered by this source.

3.4.3.2. PV system

The size of the PV system is limited by the available rooftop area facing south, which can only provide a small share of the daily load of the building. By determining the maximum number of modules that can be applied, the amount of electricity supplied by the PV system can be known. The evaluation of the solar resource is made by using the PVGIS software [33] and allows to determine the yearly average optimum angle of inclination of the PV modules. The angle of inclination for the set location is 37^o and the modules are oriented towards the south (0^o azimuth).

The dimensions of the south oriented roof are 13 meters wide by 62.5 meters long with an inclination of 9^o. With these dimensions, 62 panels fit side by side in the length of the building. In order to determine how many rows can be installed, it is necessary to take into account a certain interrow spacing to avoid shading and consequently underperformance of the system.

The first step is to calculate the height difference (h) from the back of the module to the surface. As the rooftop surface has a 9^o inclination, the tilt angle (θ) in relation to the roof corresponds to 37^o-9^o = 28^o.

$$h = \sin(\theta) \times w_m = 0.78\ [m] \qquad (10)$$

With module width (w_m) corresponding to approximately 1.67 m.

Next step is to determine the module row spacing (RS_m), which is done by first defining the solar altitude (α), also designated as sun elevation angle. The sun elevation angle over a year for the location Utrecht, De Bilt is presented in Figure 10 [34]. The green line present in the chart corresponds to the period between 9 am and 3 pm for the winter solstice, the worst case scenario (lowest number of solar irradiation hours). PV arrays need to be unshaded for at least 6 hours during the day in order to produce the most electricity. In the period between 9 am and 3 pm shading needs to be avoided since this is the period in which most of the solar radiation is available and when the system reaches its peak power [35].

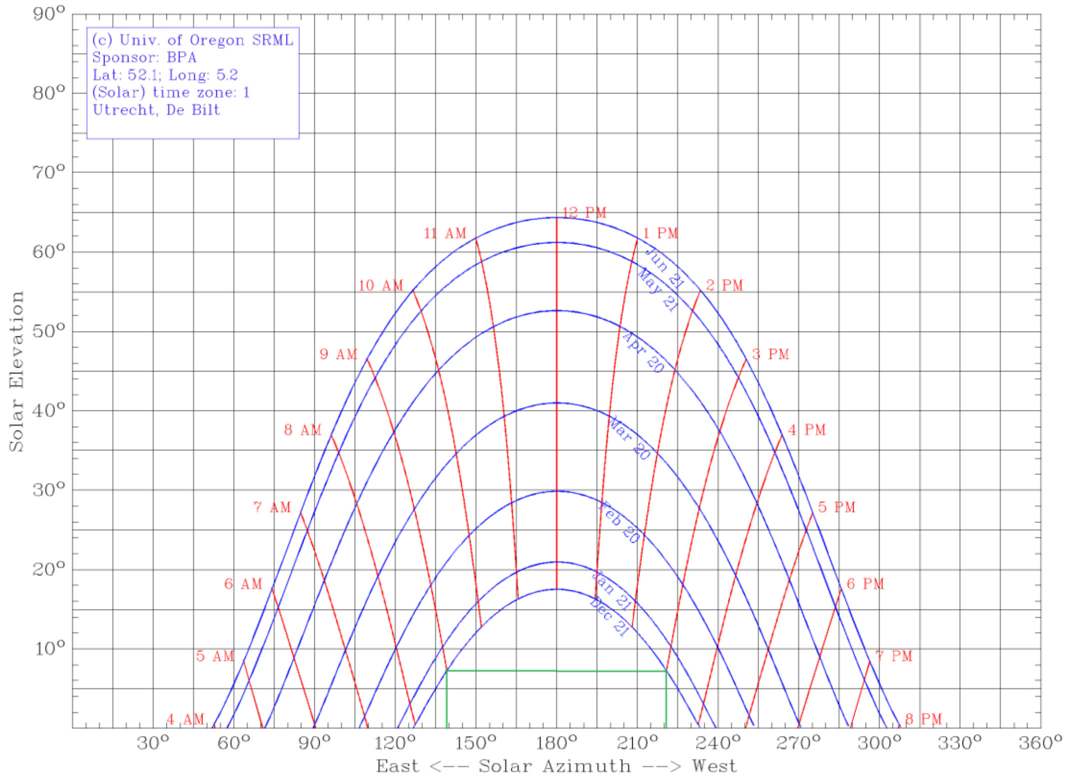

Figure 10 - daily solar path for different days of the year in De Bilt, Utrecht

The module row spacing (RS_m), following trigonometric, corresponds to:

$$RS_m = \frac{h}{\tan(\alpha)} = 5.9\ [m] \tag{11}$$

With $\alpha = 7.5^o$ being the solar elevation angle at 9 am and 3 pm.

Finally, a correction for the azimuth angle must be applied in order to determine the minimum module row spacing ($RS_{min,m}$). The azimuth correction angle (γ_c) is approximately 40^o, as shown by the green lines in Figure 14. So, the interrow spacing between arrays of modules needs to be of at least:

$$RS_{min,m} = RS_m \times \cos(\gamma_c) = 4.5\ \ [m] \tag{12}$$

Knowing the space between rows and the width of the rooftop, only two rows of PV modules are possible to install. Thus, the maximum amount of PV modules to be mounted on the roof is 124.

Several PV systems will be studied with the aim of determining the one with the lowest investment cost (€/kWh). The PV systems considered are summarized in Table 3.

Table 3 - PV systems properties. Source: [36].

PV systems								
Model	**Module type**	**Nº panels p/ system**	**Rated Power (kW)**	**Efficiency (%)**	**Area (m²)**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
FVE 250	KPV 255	1	0.255	15.43	1.65	628	25	Innov Sun
FVE 500		2	0.510	15.43	3.31	1,088		
FVE 1000		4	1.020	15.43	6.61	2,201		
FVE 1500	KPV 250	6	1.500	15.12	9.92	3,423		

3.4.4. Structural change Cases

These cases study variations in building performance when structural changes in the building envelope are applied. More specifically, structural changes considered refer to the variation of WWR.

In the reference case, the average WWR is 41% (40% south façade; 43% north façade; 41% west façade; 39% east façade). The developed cases consider the following possibilities: WWR is reduced to approximately half - average WWR = 20% (W20 case); WWR is approximately doubled – average WWR = 80% (W80 case).

Applying the same proportionalities for each façade orientation, the WWRs of the W20 case are 19% for the south façade, 22% for the north façade, 20% for the west façade and 18% for the east façade. For the W80 case the WWRs are 79% for the south façade, 82% for the north façade, 80% for the west façade and 78% for the east façade. The WWR and area of windows for both cases are presented in Table 4.

Table 4 - WRR and window area for the reference case and for W20 and W80 cases

Structural change cases - WWR						
Orientation	**Reference**		**W20**		**W80**	
	WWR (%)	**Glazing area p/ floor (m2)**	**WWR (%)**	**Glazing area p/ floor (m2)**	**WWR (%)**	**Glazing area p/ floor (m2)**
South	40	75.0	19	35.6	79	148.1
North	43	80.6	22	41.3	82	153.8
West	41	31.5	20	15.4	80	61.4
East	39	30.0	18	13.8	78	59.9

3.4.5. External factors Cases

In this section, the quantification of external factors that affect building thermal performance is described. The first factor is climate change, which can be especially relevant in long term simulations for reasons previously explained. The approach is done by taking into consideration two different scenarios taken from the Royal Netherlands Meteorological Institute. The second factor is inter-building effects, this is, the mutual shading between the reference building and the surrounding buildings. The analysis is performed by taking into account an arrangement of a typical Dutch city that considers a defined distance between buildings and a defined height of surrounding buildings.

3.4.5.1. Climate Change

Since the simulations performed for the different building solutions are mostly long term measurements (as far as 75 years for insulation), it is relevant to study weather changes instead of assuming the current climate. Thus, the temporal horizon assumed for climate change scenarios is the year 2050: if, e.g., a measure of insulation is applied in the current year, 2016, and its energy performance evaluated for the next 75 years (until 2091!), it is reasonable to assume a weather file for an intermediate year around 2050. In both cases, reference or climate change cases, the energy performance of the building is assumed to remain unchanged over time.

In order to account for climate change, the weather file used for the reference scenario in 2016 (a typical year obtained by meteorological observations from 1981-2010) is modified according to different scenarios developed by the Royal Netherlands Meteorological Institute (KNMI). Two of the four scenarios are considered: the most optimistic (G_L) and the least optimistic (W_H) [37]. The KNMI scenarios consist on four combinations of two possible values for the global temperature rise, “Moderate” (G) and “Warm” (W), and two possible changes in the air circulation pattern, “Low value” (L) and “High value” (H). The four scenarios of climate change have the same reference period as the original weather file (1981-2010).

After the scenarios are chosen, the next step is to modify the original weather file in accordance to their predictions. According to KNMI, the overall trends registered are: temperature will continue to rise, precipitation will increase, changes in wind speed are negligible and solar radiation at the earth’s surface will slightly increase. Since data about relative humidity is not given and cannot be translated from precipitation data and changes related to wind are not significant, only the variation of temperature and radiation are considered.

Case G_L:

A mean temperature change of +1.0ºC in comparison to the reference and a mean incoming solar radiation change of +0.6% are considered [37].

Case W_H:

A mean temperature change of +2.3ºC and a mean incoming solar radiation change of +1.2% are considered [37].

3.4.5.2. Inter-building shading

Mutual shading between buildings affects the reference building thermal behavior in the sense that these surrounding buildings can block a substantial part of the solar radiation, thus reducing the solar heat gains of the reference. The reduction of solar heat gains is a desired effect during summer months (cooling demand will be lower) but an unwanted effect during winter months (heating demand will be higher). This type of cases allows to evaluate the impact of the effect aforementioned.

In order to assess the impact of shading created by the surroundings, a realistic scenario for the urban environment of the Netherlands is developed. This scenario (SB) is a case in which the neighboring buildings have equal height of the reference and a distance of 25 m between the reference and the other buildings. The distance was defined by empirical observation of several streets in Google maps in the city of The Hague.

3.4.6. Combination Case

The case that is described in this sub section is the result from the combination of building solutions and external factors. This case was defined after the results from all the individual cases (presented in Chapter 4) were obtained, in order to evaluate which possible combinations would be more interesting and realistic. The case (CC) corresponds to the combination of the most profitable building solutions of insulation and glazing with the most optimistic climate change scenario for 2050 and the building shading that depicts the Dutch urban reality.

Case CC: Combination of I.1+G.1+SB+G_L cases.

This case is intended to represent an example of the many possible combinations that could be studied and analyzed.

3.5. Inputs

The following input parameters correspond to data that remains constant and is used throughout all the project for every simulation. The only exception to this corresponds to the lighting schedule, which varies in the case studies in which glazing area is subject to change and inter-building shading is considered.

Weather data:

The weather file used for the project is available in IDA ICE database and was taken from 2009 ASHRAE handbook – Fundamentals [38]. The ASHRAE database contains typical weather files for 3012 locations, providing climatic design information used for design and sizing of equipment. Design conditions are provided for locations in which long-term hourly observations are available, between 1982 and 2006. For this study, the Utrecht weather file is used.

Controller Set points:

To guarantee thermal comfort, ranges of values for temperature, mechanical supply and return air flow, relative humidity, level of CO_2 and illuminance at work place need to be defined. The European norm EN 15251 "Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics" [27] is used to set the limits of the comfort parameters. Data is collected for category II (PPD< 10% and -0.5<PMV<0.5).

The temperatures for an open space office for an activity level of 1.2 met ranges from 20 ^oC in the heating season (1.0 clo – typical clothing during winter) to 26 ^oC in the cooling season (0.5 clo – typical clothing during summer). This temperature range of comfort is set two hours before and after occupation on workdays (6h to 19h). During the rest of the hours and weekends, temperature limits are offset by 5ºC: 15ºC minimum temperature and 31ºC maximum temperature.

The design ventilation rates correspond to the sum of two components: ventilation for pollution from the occupants (bio effluents) and ventilation for the pollution from the building and systems. For the first component, 7 l/(s.person) are needed, corresponding to 0.45 l/(s.m^2) since the number of occupants is defined to be 0.064 person/m^2, as will be described further ahead. For the second component, values vary between 0.35 l/(s.m^2) and 1.4 l/(s.m^2). Given this, the mechanical supply and return air flow must be between 0.8 l/(s.m^2) (very low polluting building) and 1.85 l/(s.m^2) (non low polluting building). Mechanical air supply is variable between these ranges in order to control humidity. Relative humidity must be between 25% and 60% while CO_2 levels must be between 350 ppm and 800 ppm. Illuminance is defined to be constant at 500 lux, the recommended value for an open space office.

Internal gains:

• Occupants:

0.064 person/m^2 or 8 W/m^2, in order to comply with recommendations for office buildings [39]. This means that in the whole office building, there are 618 people distributed evenly for each of the six floors (103 people per floor). The activity level is considered to be 1.2 met (126 W), typical for an office building in accordance to EN 15251. The clothing is in the range of 0.5-1 clo, which the program calculates automatically: the PMV at which the occupant wears maximum clothing is -1 and the PMV at which the occupant wears minimum clothing is 1. The schedule of occupation of the building is in weekdays, from 8h to 17h.

• Equipment:

To simplify all the possibilities of equipment that can exist in an office building, a value of 15 W/m^2 is defined for an office building considered having modern equipment with low consumption [39]. The schedule of operation is the same as the occupation schedule of the offices.

• Lighting:

Lighting requirements are 500 lux (or lm/m^2), corresponding to the typical recommended task illuminance for offices [16]. The floor area of office room is 1,600 m^2, meaning 800 thousand lm are necessary for a good illuminance. Considering a regular tubular LED lamp of 80 W with 8,000 lm each, each floor needs about 100 of these lamps or 0.06 lamps/m^2 or even 5.0 W/m^2, with a luminous efficacy of about 100 lm/W.

The schedule for the lights from 8h to 17h on workdays was divided according to the seasons: winter, spring, summer and fall. This way it is possible to adjust artificial lighting to daylight availability, thus reducing electricity consumption. For each season, one representative day was chosen (15th February, 16th May, 15th August and 15th November) and its daylight availability was evaluated through simulation in IDA ICE. For each hour of the day between 8h and 17h, the average illuminance in lux is obtained. This way, it is possible to determine what fraction of the total lamps is needed to achieve a level of illuminance of 500 lux in the office room. Figure 11 represents the reference lighting schedule defined for spring on a workday. From 8h to 9h, 70% of the lights should be on, while from 9h to 10h 60%, from 10h to 11h 50%, from 11h to 12h and from 16h to 17h 40% and from 12h to 16h only 30% of the lights are necessary.

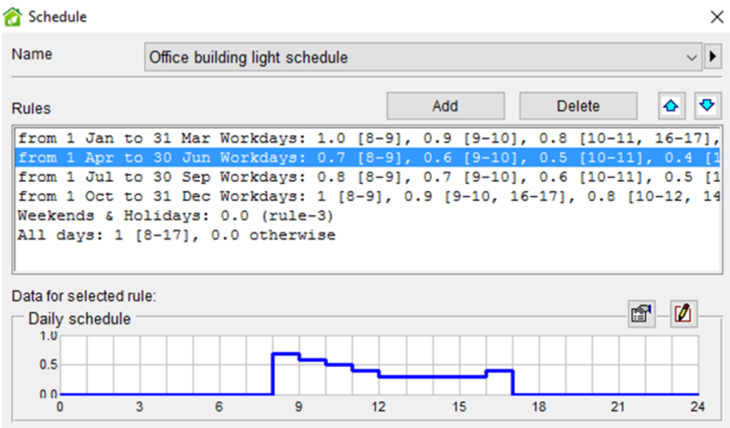

Figure 11 - Lighting schedule for a typical spring day

Supply air temperature:

Supply air used to ventilate the rooms is set to enter the indoor environment within a range of temperatures between 15 ºC and 21 ºC. These values follow from a study of strategies for supply air temperature control in office buildings [40]. The boundaries were defined to comply with recommendations to avoid thermal discomfort and that air enters too dry/humid.

Emissions:

Primary energy for electricity generation in the Netherlands in 2012 consisted of 54.4 % of natural gas, 26.6% of coal, 8.7% of biofuels and waste, 4.9% of wind, 3.8% of nuclear, 1.1% of oil, 0.4% of solar and 0.1% of hydro. Average emission for electricity production was around 419 gCO_2/kWh, according to IEA report for the Netherlands 2014 [41]. The primary energy conversion factor for electricity in the Netherlands is 2.56 [42]. This information is filled in the following electric energy meters of the simulation program: lighting, equipment and electric cooling and heating.

For fuel heating and hot domestic water, a fuel meter is used. The fuel is assumed to be natural gas, but any other fuel can be used. Carbon emissions for natural gas have an average for OECD countries of 400 gCO_2/kWh [43]. This average value is used since there is no information available of natural gas emissions in the IEA report for the Netherlands. The primary energy conversion factor is considered to be 1.

In case of electricity production from wind or solar energy. emissions are considered to be null and the primary energy conversion factor 2.56, as any other source used to produce electricity.

Cost of Energy:

The electricity price (€/kWh) is taken from Central Bureau of Statistics of the Netherlands [44]. The electricity price for the smallest non-household consumption class (between 20 and 500 MWh) is 0.119 €/kWh for the year of 2014. The natural gas price (€/kWh) is taken from the same source as the electricity price. The natural gas price for the smallest non-household consumption class (between 278 MWh and 2778 MWh) is 0.065 €/kWh for the year of 2014.

3.6. Outputs

Once all the inputs are filled into the program, the simulation is ran. This simulation gives several outputs that need to be translated into performance indicators. Other outputs are only needed to validate that the comfort requirements are met, e.g., internal temperature, Fanger's comfort indices and indoor air quality.

The required outputs for evaluating energy performance are:

- Energy load for zone heating/cooling, AHU heating/cooling (MWh). These values allow to quickly calculate, taking into account the efficiency of the installations, the electricity or fuel consumption by the installations.
- Electricity consumption of lighting and equipment (MWh). Electricity consumption by lighting is used to calculate savings or more electricity spending in case studies where light is a variable (different percentages of WWR or inter-building effects). Electricity consumption by equipment is always constant but gives an idea of its share of the total building electricity consumption.
- Energy balance (MW) is not directly used in calculations but allows to understand the magnitude and the sources of losses and gains.
- Primary energy consumption (MWh) – a direct energy performance indicator.
- Energy produced (MWh) – a direct energy performance indicator.

The required outputs for evaluating sustainability performance are:

- CO_2 emissions (tonCO_2) - a direct sustainability performance indicator.
- Primary energy consumption (MWh) -a direct sustainability performance indicator. Shows the magnitude of resources exploitation.
- Renewable energy production (MWh) - a direct sustainability performance indicator.

The simulation program does not cover most of the cost outputs. Thus, when needed, they were calculated with another software tool (Excel). The required outputs for evaluating cost performance are:

- Investment in building solutions (€), such as insulation, glazing and renewable energy technologies.
- Peak demand (MW). This output allows to choose the adequate size (capacity) of installations, thus the capital investment to acquire them.
- Cost of energy (€) - electricity or fuel.

The previous three cost outputs were then used to obtain the cost performance indicators mentioned in section 2.6: direct benefit (€), payback time (years) and net present value - NPV (€).

3.7. Sizing and Choosing of Installations

In order to translate the tool's outputs into relevant performance indicators described in the last sub-section, energy, sustainability and cost calculations need to be performed. These calculations are done after the installations are selected and sized (in terms of capacity).

Sizing

Heating and cooling peak demands for zone acclimatization and ventilation are determined in order to size the installations. To avoid oversizing, a general method to determine the installations size is using the 0.996^{th} quantile of the heating and cooling peak load for zone acclimatization, meaning that 70 h a year (35 h of PMV < - 0.5 and 35 h of PMV > 0.5), thermal comfort is not fully achieved [45]. However, Dutch requirements permit a maximum of 200 h where PMV<-0.5 or PMV>0.5 [46]. As the 0.996^{th} quantile still generates oversizing, especially for cooling, the 0.990^{th} quantile was chosen instead (175 h that thermal comfort is not met). The peak capacity for heating and cooling through air ventilation (AHU heating/cooling) was used, the reason is to avoid thermal discomfort for more than the fixed 175 h per year.

Choosing

For each building solution, including the reference, two options of supply energy are considered: heating and cooling demand is totally supplied by using electricity; heating demand is supplied by using natural gas and cooling demand is supplied by using electricity.

For the first option, one product is chosen from the inventory to supply heating and cooling to zones (air conditioning devices) and another one to supply heating and cooling to the AHU (water condensation heat pump). Then, a range of capacities of the selected installation is studied in order to determine which one is the best investment. The criteria for choosing the best device for each type of installation corresponds to the lowest lifetime cost of the device (initial investment + energy costs). As the same air conditioning device is used to provide both heat and cold, the number of devices chosen depends on the highest number needed for heating or cooling. For the second supply option, the same procedure is done. Zone heating is provided by boilers that distribute heat to water radiators; Zone cooling is provided by air conditioning devices; AHU heating is again provided by boilers; AHU cooling is provided by water condensation chillers. Table 5 summarizes the type of installation selected for each considered option of energy supply.

Table 5 - Energy supply options considered for each building solution.

Energy supply option	All electric (Option 1)	Fuel + electricity (Option 2)
Installations	Zone heating and cooling – air conditioning devices AHU heating and cooling – heat pump	Zone heating – Gas boiler + radiators Zone cooling – Air conditioning devices AHU heating – Gas boiler AHU cooling – Chiller

3.8. Cost calculations

Energy and sustainability indicators can be directly obtained from the simulation's outputs once the adequate installations are chosen. However, cost indicators can only be obtained by translating the cost outputs into parameters that assess cost-effectiveness. Investment in building solutions can be directly obtained from the inventory while the cost of energy is given as output from the program and the type and capacity of installations are defined by following the process described in the last sub-section (3.7). These three cost outputs are used to determine the direct benefit, payback time and NPV.

The simulation of building performance is done for the life span of the solution with the longest lifetime. Thus, this is the lifetime of the project on which the economic indicators are based.

Direct benefit (B) calculations take into consideration the investment on altering the building envelope and its impact on energy consumption and equipment sizing. These calculations are made using the following equation:

$$B = nE_{av}C + \sum(\Delta I_i) - \Delta I_m \ [€] \tag{13}$$

Where n is the number of years of project implementation, E_{av} is the energy consumption avoided (kWh) in comparison to the reference, C is the cost of energy (€/kWh), ΔI_i is the difference between the investment on installations in the case study and the investment on installations in the reference case and ΔI_m is the difference between the investment on the solution applied in the case study and the investment on the solution of the reference case. If benefit is a positive value, this means the measure is cost-effective.

Apart from measuring the benefit of a building solution, payback time and net present value are variables of interest for determining project profitability [47]. Payback time (PB) refers to the period of time required to recover the investment made and can be calculated through the following equation:

$$PB = \frac{\Delta I}{B_{an}} \ [years] \tag{14}$$

Where ΔI is the sum of the absolute values of ΔI_i and ΔI_m (€) and B_{an} is the benefit of the annual energy savings (€/year).

So far, the value of money over the time has not yet been accounted for, thus possibly giving misleading outcomes. NPV takes this into consideration and is obtained by calculating the costs and benefits for each period of an investment (cash flows). It is used to determine whether a project or investment will result in a net profit or a loss. A positive value indicates that a project is profitable. NPV can be calculated through the following equation:

$$NPV = \sum \frac{C_n}{(1+i)^n} - C_0 \ [€] \tag{15}$$

Where C_n is the annual cash flow (€) of the year n, C_o is the annual cash flow (€) of the year 0 and i is the annual discount rate (%). Cash flows account for reinvestment in technologies with a shorter lifetime than the life span of the project.

Chapter 4 – Results

In the current chapter, the results for each building solution are presented. The cases are compared to the reference by analyzing them in terms of energy, sustainability and cost performance. The performance assessment is executed by using the indicators previously described.

4.1. Reference Case

The following results characterize in detail the building solution adopted as the reference case. These results are also used as the base of the performance analysis done for the other building cases.

Sizing and selection of installations

Heating and cooling loads for zone acclimatization and for ventilation are determined in order to obtain the capacity of the installations. The results for the simulation of the reference case is shown in Table 6.

Table 6 - Heating and cooling load for zone acclimatization and ventilation for the reference case

Load (kW)	
Zone Heating	898
ZH 0.990th	278
AHU heating	94
Zone Cooling	230
ZC 0.990th	34
AHU cooling	180

Heating and cooling yearly energy demand that provides thermal comfort to the occupants is shown in Table 7.

Table 7 - Heating and cooling yearly energy demand for the reference case

Energy demand (MWh)	
Zone Heating	64
Zone Cooling	10
AHU heating	74
AHU cooling	14
Total Heating	138
Total Cooling	24

The annual energy demand is then applied to calculate fuel or electricity consumption of the installations, according to the energy supply option selected. The data presented in the last two tables is used to select the installations for both supply options, which are presented in Table 8 and 9.

Table 8 - Selected installations that provide heating and cooling for the reference case in which supply energy is all electric. In blue, the number of air conditioning devices installed - as the same device is used to provide both heat and cold, the number of devices chosen depends on the highest number needed for heating or cooling

Reference Case - Option 1: Heating Electric + Cooling Electric							
Equipment and energy consumption for zone heating and cooling							
Model	**Nr Heating units**	**Nr Cooling Units**	**Invest Equip (t €)**	**Elec heating (MWh)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
PSH-P140i	18	6	143	18	3	3	181
Equipment and energy consumption for AHU heating and cooling							
EWWP185	1	1	27	16	4	2	63

Table 9 - Selected installations that provide heating and cooling for the reference case in which supply energy is both fuel and electricity. The same boiler can be used in both zone heating and supply air heating, thus the number of boilers needed is not rounded to the unit. The sum of both values determines the number of boilers needed.

Reference Case - Option 2: Heating Fuel + Cooling Electric						
Equipment and energy consumption for zone heating						
Model	**Nr Boilers**	**Nr Radiators**	**Invest Equip (t €)**	**Fuel heating (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
GB312-200+REV3.2	1.39	90	117	58	4	174
Equipment and energy consumption for cooling						
Model	**Nr Cooling Units**		**Invest Equip (t €)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
PSH-S60i	6		23	2	0.2	26
Equipment and energy consumption for AHU heating						
Model	**Nr Boilers**		**Invest Equip (t €)**	**Fuel heating (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
GB312-200	0.47		0	68	4	66
Equipment and energy consumption for AHU cooling						
Model	**Nr Cooling Units**		**Invest Equip (t €)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
EWWP185	1		27	4	0.5	35

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Table 6 and 7 respectively. Annual energy consumption for heating and cooling and annual energy consumption for lighting and equipment are presented in Table 10. Annual primary energy demand is presented as a sustainability indicator.

Table 10 - Annual energy consumption for heating, cooling, equipment and lighting for each supply option for the reference case

Energy consumption (MWh)	Supply Option 1	Supply Option 2
Electricity Lighting	71	71
Electricity Equipment	338	338
Fuel/Elec Heating	34	126
Electricity Cooling	7	6

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating, cooling and lighting are presented in Table 11. Primary energy demand and respective emissions for other energy usages are not shown since they are constant throughout the whole project. No renewable energy production is considered for the reference case.

Table 11 – Primary energy demand and CO_2 emissions for heating, cooling and lighting for each supply option for the reference case

	Supply Option 1	**Supply Option 2**
Primary Energy (MWh)		
Heating	88	126
Cooling	18	14
Lighting	182	182
CO_2 emissions (ton CO_2)		
Heating	14	50
Cooling	3	2
Lighting	30	30

Cost indicators

Capital investment on installations and annual energy bill are presented in Table 12. Capital investment on insulation and glazing are shown in Table 13. These values will serve as reference for the other cases in order to obtain the direct benefit, payback time and NPV of the measures applied on those cases.

Table 12 – Annual energy bill for heating, cooling and lighting and investment on installations for each supply option for the reference case

	Supply Option 1	**Supply Option 2**
Annual Energy Bill (t €)		
Heating	4	8
Cooling	0.8	0.7
Lighting	8	8
Investment on installations (t €)		
Heating	170	117
Cooling		51

Table 13 - Capital investment on insulation and glazing for the reference case

Capital investment (t €)	
Insulation	95
Glazing	142

4.2. Insulation Cases

Sizing and selection of installations

The sizing and selection of the installations for these cases are performed by applying the same procedure as in the reference case. Note that installations chosen for each case may vary, since the installation with the lowest lifetime cost is the one considered. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 12. The absolute values of load and energy demand and the chosen installations are presented in Tables B-3 to B-14 of the Appendices.

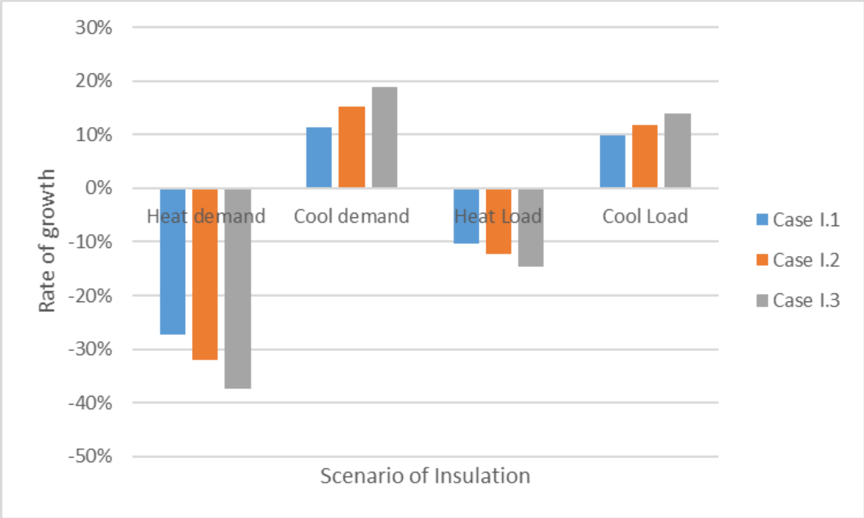

Figure 12 - Annual heat and cool demand and heat and cool load for each insulation case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 12. Annual energy consumption for heating and cooling for both supply energy options are depicted in Figure 13 while annual energy consumption for lighting and equipment are unchanged. Annual primary energy demand is presented as a sustainability indicator.

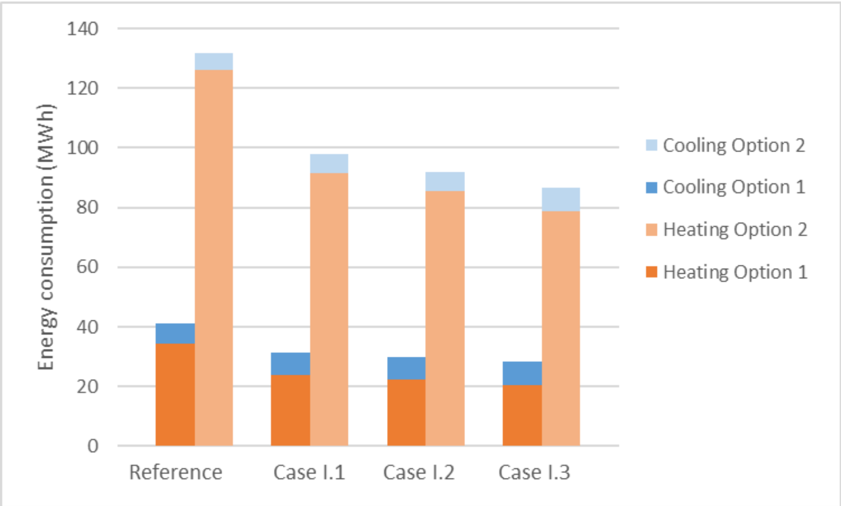

Figure 13 - Annual energy consumption for each case of insulation and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 14 and 15, respectively. Lighting energy demand and emissions remain unchanged for these cases.

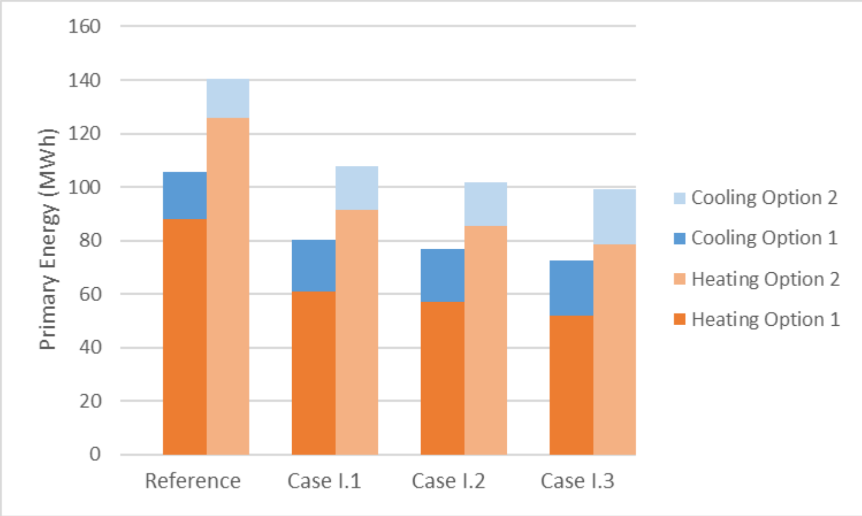

Figure 14 - Annual primary energy demand for each case of insulation and the reference for both energy supply options

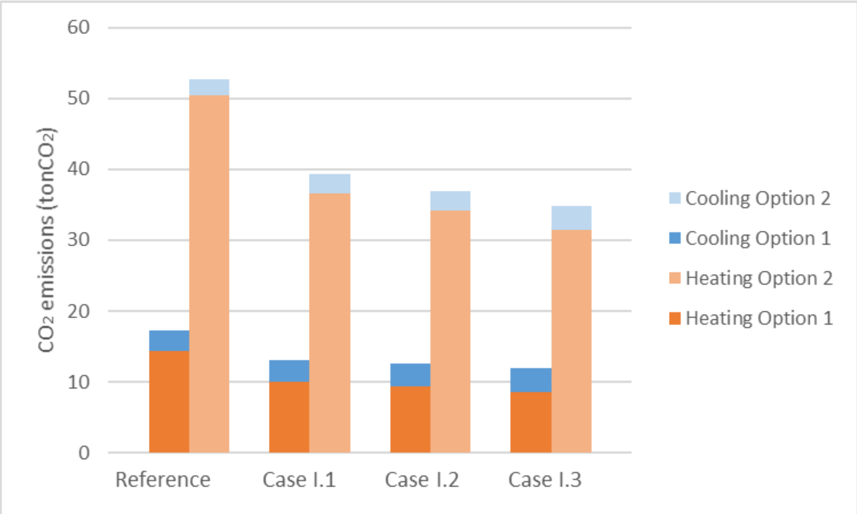

Figure 15 - Annual CO_2 emissions for each case of insulation and the reference for both energy supply options

Cost indicators

Cost indicators for each case of insulation, considering both supply energy options, are illustrated in Figure 16 and 17. These indicators are calculated for the project lifetime which is considered to be, for insulation cases, 75 years (lifetime of insulation [19]). Thus, installations are considered to be replaced every 15 years. As explained in section 3.8, ΔI_i corresponds to the difference between the total investment on installations in the insulation cases and in the reference; E_{av} accounts for fuel/electricity savings in comparison to the reference; ΔI_m corresponds to the difference between initial investment on each insulation case (Table 14) and in the reference (Table 13); B is the benefit of the project without accounting for the value of money over time. For NPV calculations, a nominal annual discount rate of 3% is considered, since it is a long term project with a low risk. The real discount rate is 1.3%, obtained by adjusting the nominal discount rate with an inflation rate at 1.7% in the Netherlands (average rate of the 2006-2015 period) [48].

Table 14 – Capital investment on insulation for each case

Capital investment on insulation (t €)	
Case I.1	158
Case I.2	210
Case I.3	269

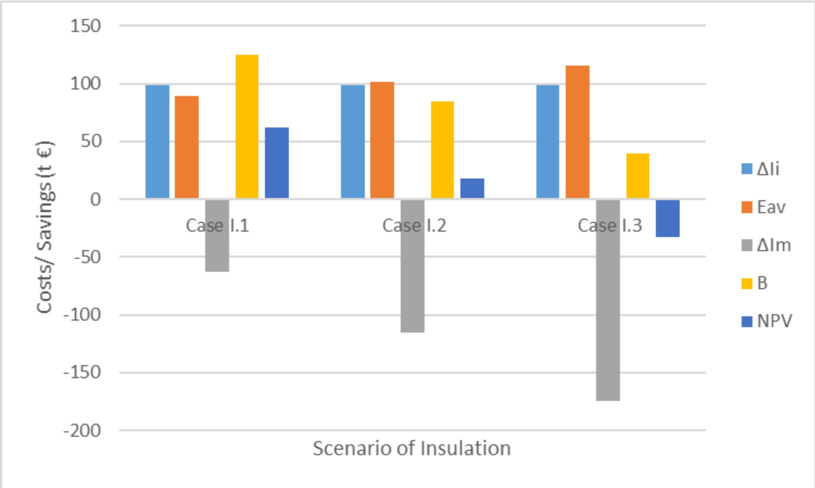

Figure 16 - Cost indicators for each insulation case over the project lifetime. Option 1 - all electric supply

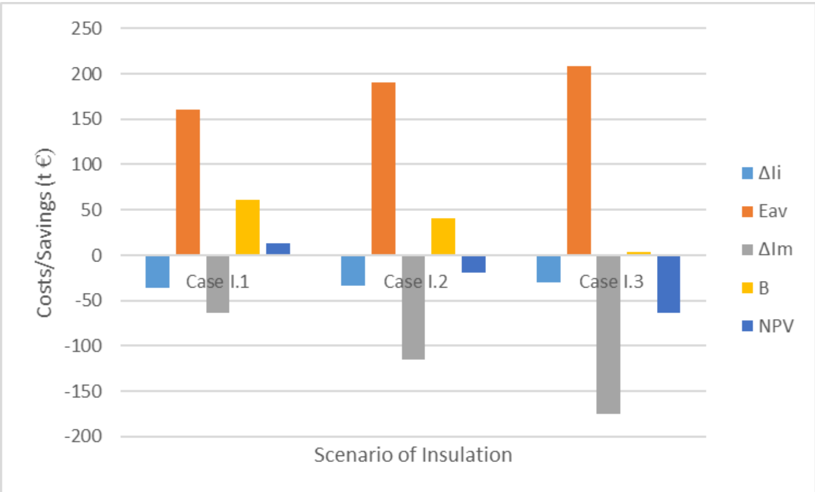

Figure 17 - Cost indicators for each insulation case over the project lifetime. Option 2 – fuel + electricity supply

Simple payback for each of the cases is presented in Table 15.

Table 15 - Simple payback for each case of insulation

Simple Payback (years)	Supply Option 1	Supply Option 2
Case I.1	0	46
Case I.2	12	59
Case I.3	49	74

4.3. Glazing Cases

Sizing and selection of installations

The sizing and selection of the installations for these cases are performed by applying the same procedure as in the reference case. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 18. The absolute values of load and energy demand and the chosen installations are presented in Tables B-15 to B-22 of the Appendices.

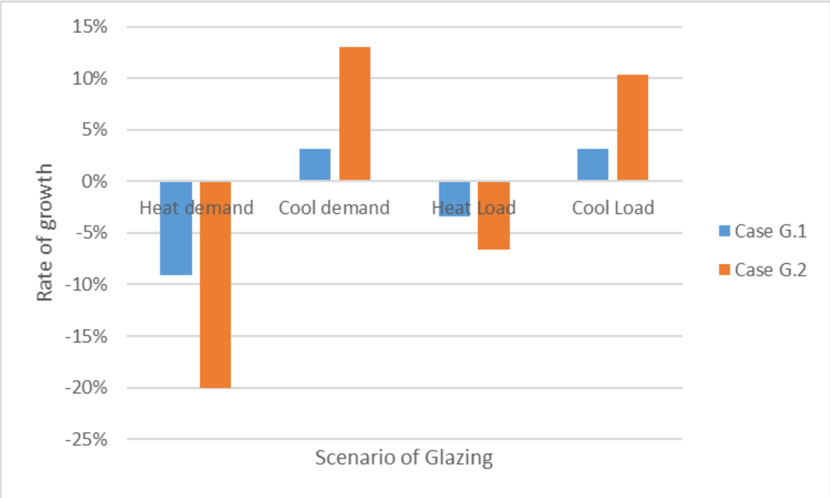

Figure 18 - Annual heat and cool demand and heat and cool load for each glazing case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 18. Annual energy consumption for heating and cooling for both supply energy options are depicted in Figure 19 while annual energy consumption for lighting and equipment are unchanged. Annual primary energy demand is presented as a sustainability indicator.

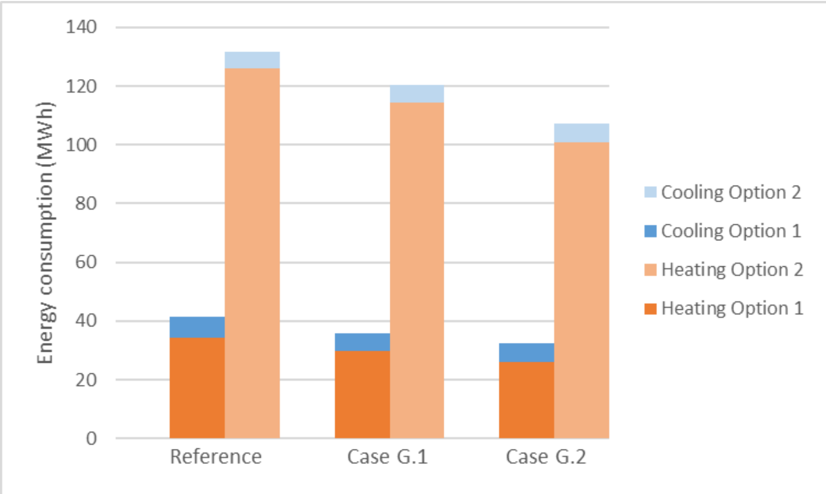

Figure 19 - Annual energy consumption for each case of glazing and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 20 and 21, respectively. Lighting energy demand and emissions remain unchanged for these cases.

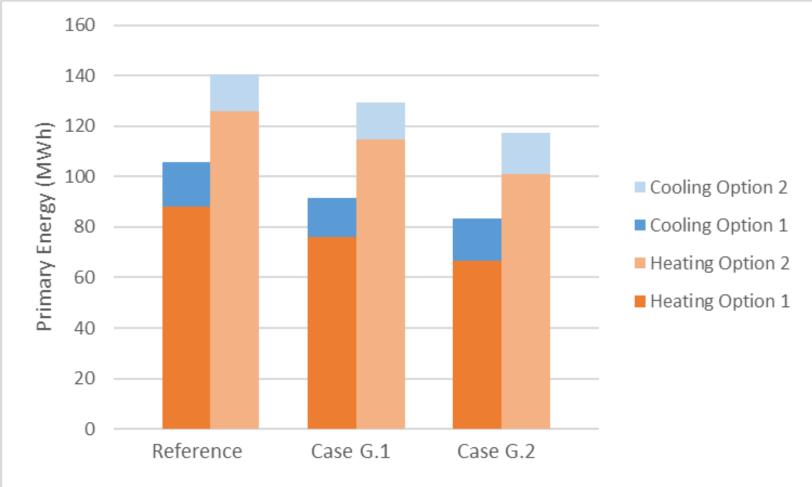

Figure 20 - Annual primary energy demand for each case of glazing and the reference for both energy supply options

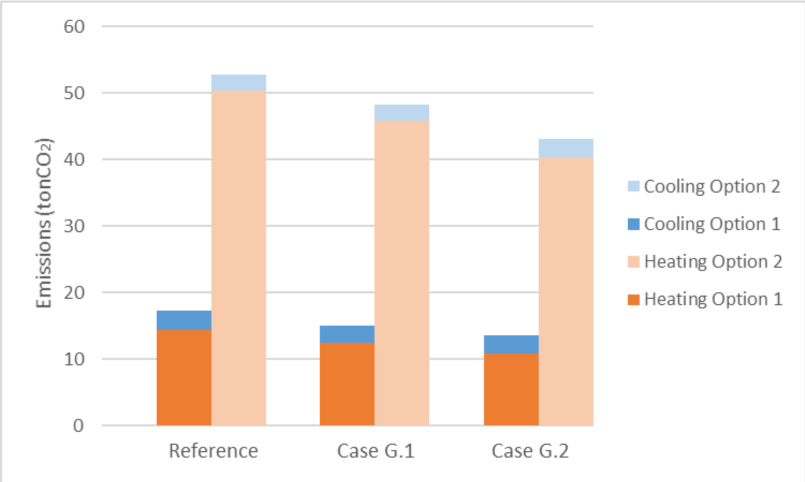

Figure 21 - Annual CO_2 emissions for each case of glazing and the reference for both energy supply options

Cost indicators

Cost indicators for each case of glazing, considering both supply energy options, are illustrated in Figure 22 and 23. These indicators are calculated for the project lifetime which is considered to be, for glazing cases, 30 years (lifetime of double glazing [19]). Thus, installations are considered to be replaced every 15 years. ΔI_m is the difference between initial investment in each glazing case (Table 16) and in the reference (Table 13). For NPV calculations, a nominal annual discount rate of 5%, translated into a real discount rate of 3.3% is considered.

Table 16 - Capital investment on glazing for each case

Capital investment on glazing (t €)	
Case G.1	151
Case G.2	190

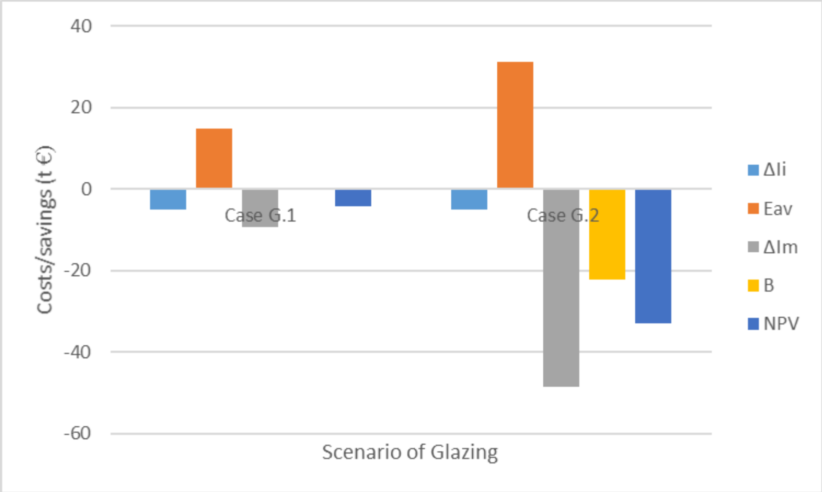

Figure 22 - Cost indicators for each glazing case over the project lifetime. Option 1 - all electric supply

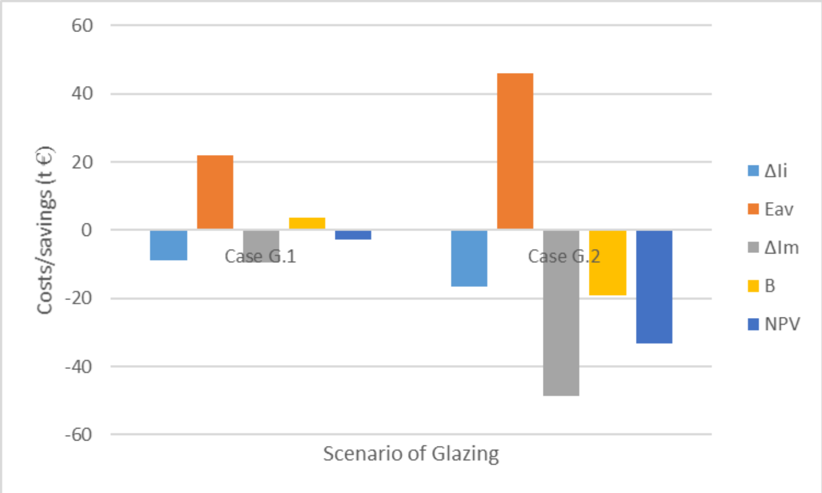

Figure 23 - Cost indicators for each glazing case over the project lifetime. Option 2 – fuel + electricity supply

Simple payback for each of the cases is presented in Table 17.

Table 17 - Simple payback for each case of glazing

Simple Payback (years)	Supply Option 1	Supply Option 2
Case G.1	29	51
Case G.2	41	43

4.4. Small wind turbines and PV system Cases

Sizing and selection of installations

Installations for both renewable energy technology cases are the same as in the reference, since the aim of RET is to supply part of the energy demand needs of the building, thus not having any effect on the thermal balance of the building.

Selection of turbines and PV systems

For both cases of RET, the selected technology is the one with the lowest cost of energy, measured in €/kWh. The choice process of small wind turbines is presented in Table 18 while the choice process of PV systems is presented in Table 19.

Table 18 - Selection process of small wind turbines. Blue indicates the type of turbine chosen

Wind Turbines						
Model	**Annual production p/ turbine (MWh)**	**Area occupied p/ turbine (m^2)**	**Nr turbines**	**Investment (t €)**	**Investment (€/W_p)**	**Cost of energy (€/kWh)**
Passaat	1.30	243	6	58	6.89	0.39
Montana	4.90	625	2	36	3.11	0.22
Alizé	10.10	992	1	43	4.31	0.24

Table 19 - Selection process of PV systems. Blue indicates the type of system chosen

PV systems						
System	**Annual production p/ module (MWh)**	**Nr modules p/ system**	**Nr systems**	**Investment (t €)**	**Investment (€/W_p)**	**Cost of energy (€/kWh)**
FVE 250	0.24	1	124	78	2.46	0.148
FVE 500		2	62	67	2.13	0.134
FVE 1000		4	31	68	2.16	0.135
FVE 1500		6	21	72	2.28	0.140

Energy indicators

The only energy indicator that is different from the reference case corresponds to annual energy production. This energy production is electricity that is supplied to the building, thus avoiding electricity consumption from the grid. Given this, electricity production can be also denominated as electricity savings, which are associated with a specific amount of primary energy avoided (saved). Both indicators are presented in Figure 24.

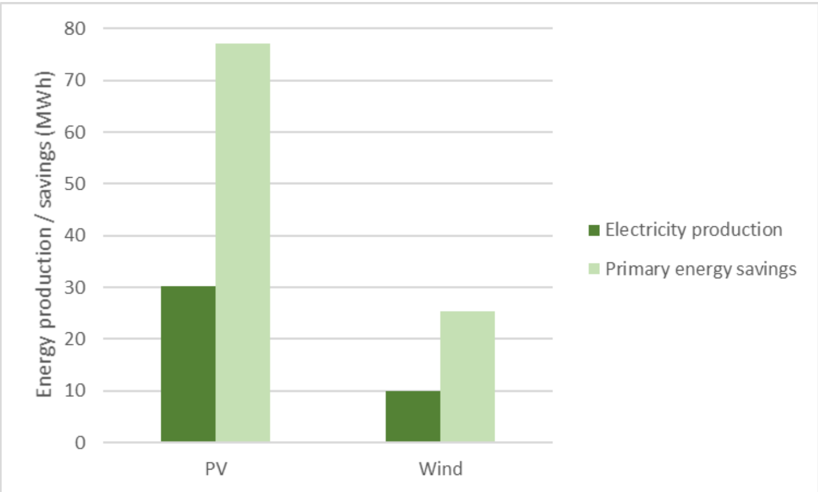

Figure 24 - Annual electricity production and associated primary energy savings for wind turbines and PV systems

Sustainability indicators

Annual primary energy savings due to renewable electricity production are already illustrated in Figure 24. CO_2 emissions avoided by self-produced zero-emission electricity are depicted in Figure 25.

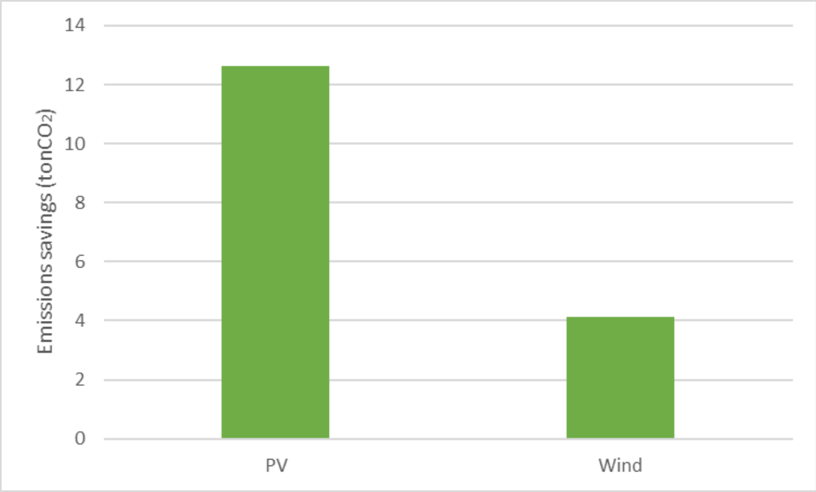

Figure 25 – Annual CO_2 emissions savings due to self-produced zero-emission electricity for wind turbines and PV systems

Cost indicators

Cost indicators for both RET are illustrated in Figure 26. These indicators are calculated for the project lifetime which is considered to be, for both cases, 25 years (lifetime of wind turbines and PV modules). E_{av} accounts for the electricity production of the technologies, thus electricity savings (consumption from the grid avoided); I_m corresponds to investment on the technologies - 36 thousand € for wind turbines and 67 thousand € for PV systems (with an additional O&M annual cost fixed at 2% of the capital investment), as indicated in Table 18 and 19 respectively. Again, for NPV calculations, a nominal annual discount rate of 5%, translated into a real discount rate of 3.3% is considered.

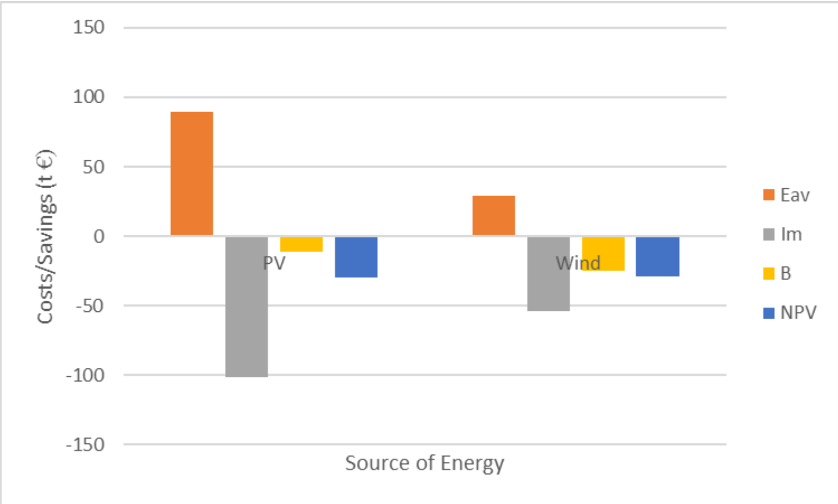

Figure 26 - Cost indicators for each renewable energy technology over the project lifetime

Simple payback for each of the cases is presented in Table 20.

Table 20 - Simple payback for each RET case

Simple payback (years)	
PV	28
Wind	46

4.5. Structural Cases

Sizing and selection of installations

The sizing and selection of the installations for these cases are performed by applying the same procedure as in the reference case. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 27. The absolute values of load and energy demand and the chosen installations are presented in Tables B-23 to B-30 of the Appendices.

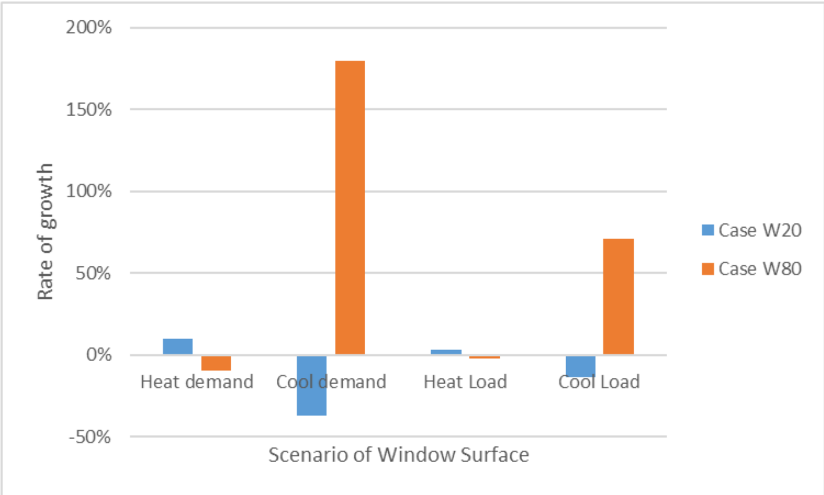

Figure 27 - Annual heat and cool demand and heat and cool load for each WWR case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 27. For this type of cases, electricity consumption for lighting suffers variation from the reference. Annual energy consumption for heating, cooling and lighting for both supply energy options are depicted in Figure 28. Annual primary energy demand is presented as a sustainability indicator.

Figure 28 - Annual energy consumption for each WWR case and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 29 and 30, respectively.

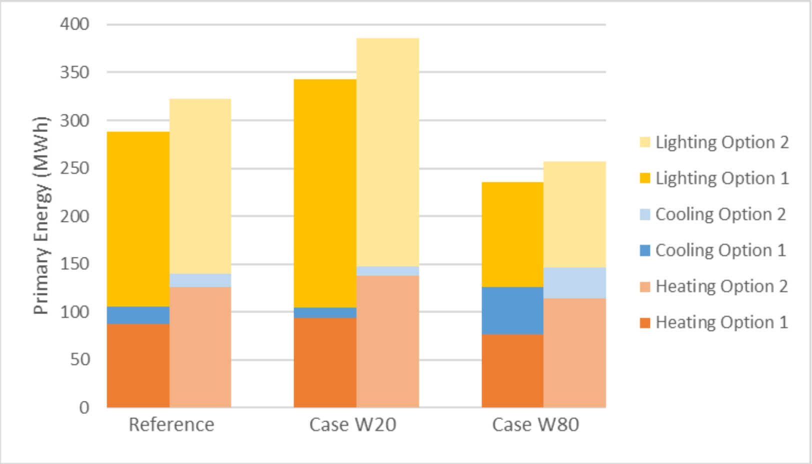

Figure 29 - Annual primary energy demand for each WWR case and the reference for both energy supply options

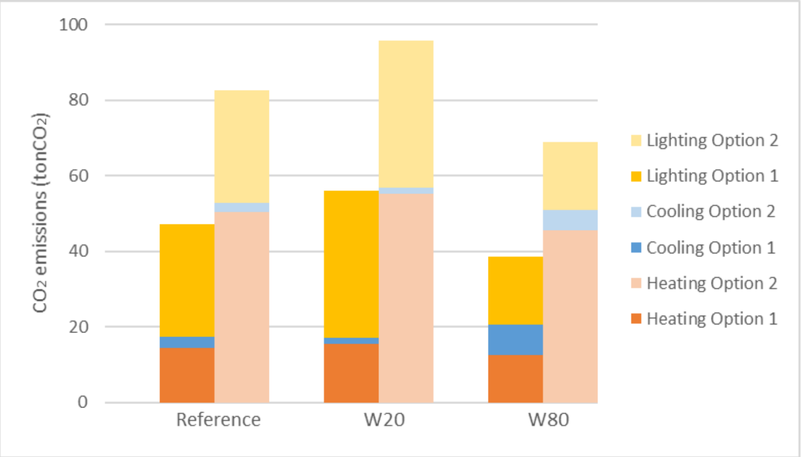

Figure 30 - Annual CO_2 emissions for each WWR case and the reference for both energy supply options

Cost indicators

Cost indicators for each WWR case, considering both supply energy options, are illustrated in Figure 31 and 32. For this type of cases, the economic performance is done in a different way – variations in investment on installations (I_i) and variations on energy bill are taken into account. Benefit, payback time and NPV cannot be calculated since there are other investment variations that couldn't be accounted for – WWR changes implies not only a different area of glazing but also a different area of wall construction; the cost of other materials than insulation present in the walls was not considered in the research. Since investment on installations is done for each period of 15 years (lifetime of installations), annual energy bill was converted into energy bill for 15 years, in order to make indicators comparable.

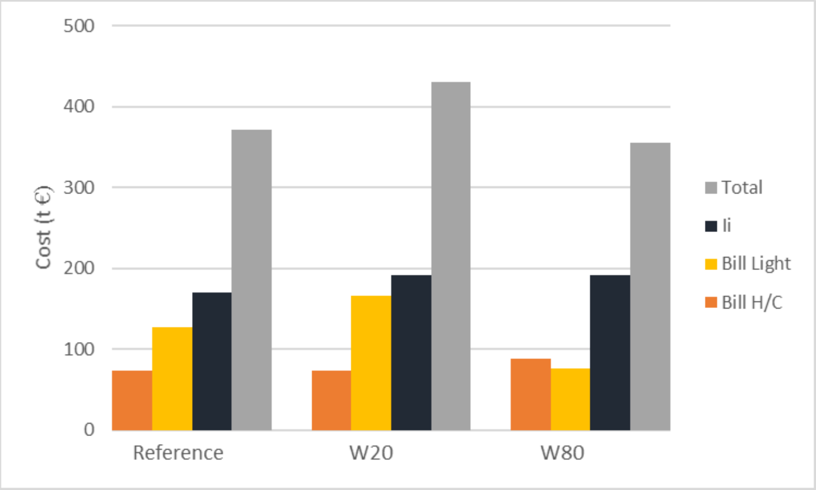

Figure 31 - Cost indicators for each WWR case over 15 years. Option 1 - all electric supply

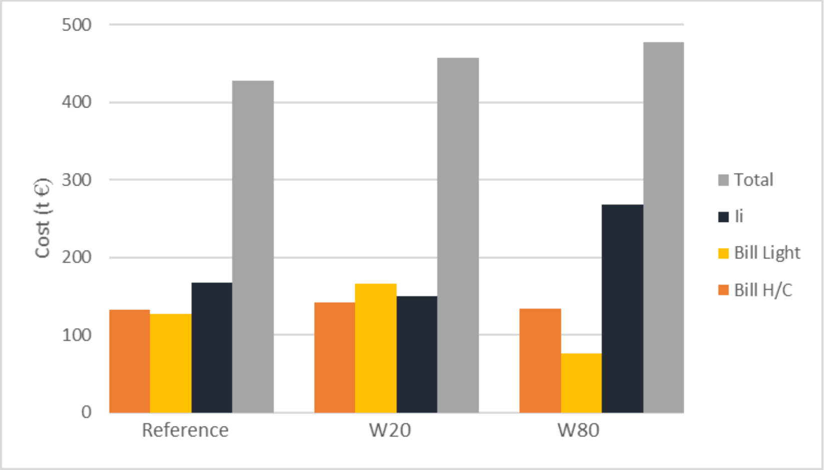

Figure 32 - Cost indicators for each WWR case over 15 years. Option 2 – fuel + electricity supply

4.6. Climate Change Cases

Sizing and selection of installations

The sizing and selection of the installations for these cases are performed by applying the same procedure as in the reference case. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 33. The absolute values of load and energy demand and the chosen installations are presented in Tables B-31 to B-38 of the Appendices.

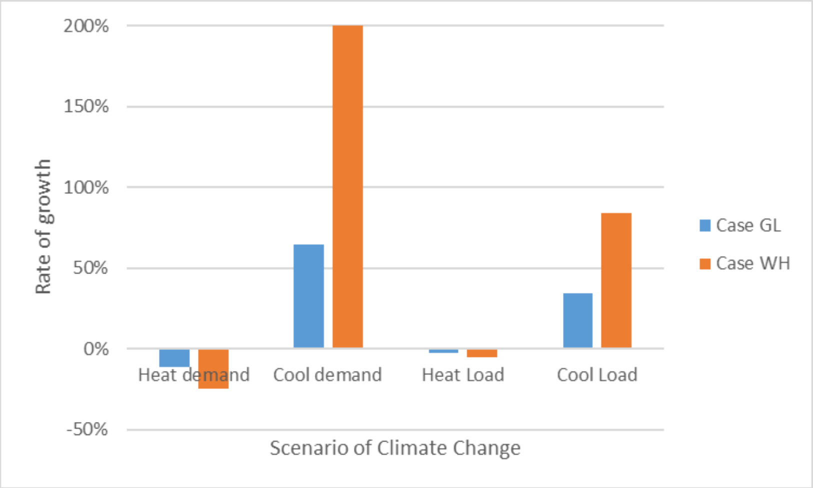

Figure 33 - Annual heat and cool demand and heat and cool load for each climate change case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 33. Annual energy consumption for heating and cooling for both supply energy options are depicted in Figure 34 while annual energy consumption for lighting remains unchanged. Annual primary energy demand is presented as a sustainability indicator.

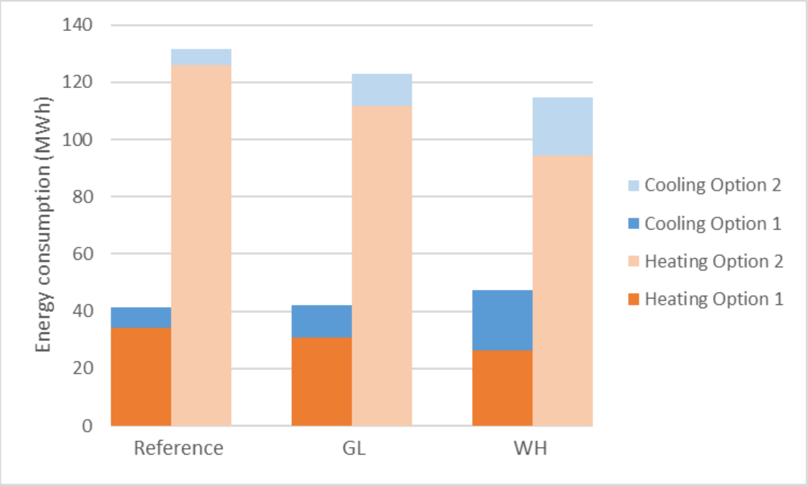

Figure 34 - Annual energy consumption for each climate change case and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 35 and 36, respectively. Lighting energy demand and emissions remain unchanged for these cases.

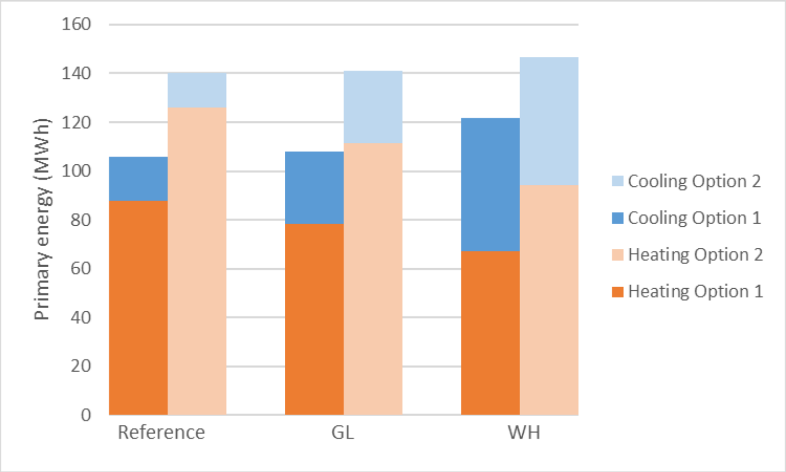

Figure 35 - Annual primary energy demand for each climate change case and the reference for both energy supply options

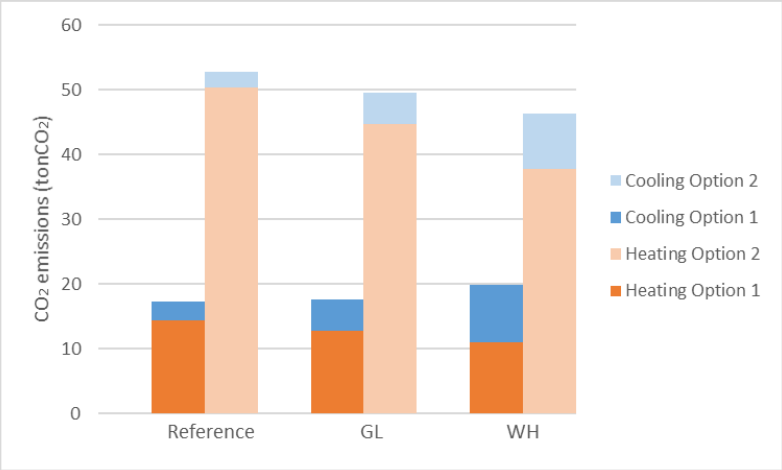

Figure 36 - Annual CO_2 emissions for each climate change case and the reference for both energy supply options

Cost indicators

Cost indicators for each climate change case, considering both supply energy options, are illustrated in Figure 37 and 38. For this type of cases, the economic performance is done in a different way – variations in investment on installations (I_i) and variations on energy bill are taken into account. Benefit, payback time and NPV cannot be calculated since climate change corresponds to an external factor, thus not any measure of retrofitting or alteration to a new building project. Since investment on installations is done for each period of 15 years (lifetime of installations), annual energy bill was converted into energy bill for 15 years, in order to make indicators comparable.

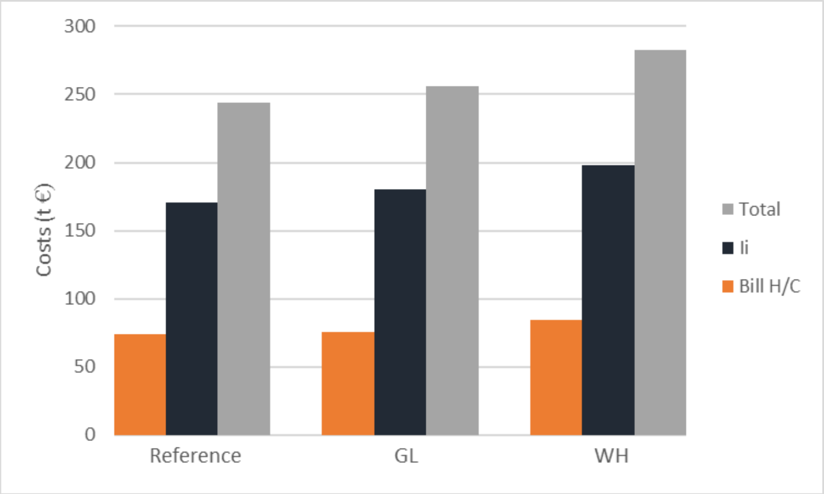

Figure 37 - Cost indicators for each climate change case over 15 years. Option 1 - all electric supply

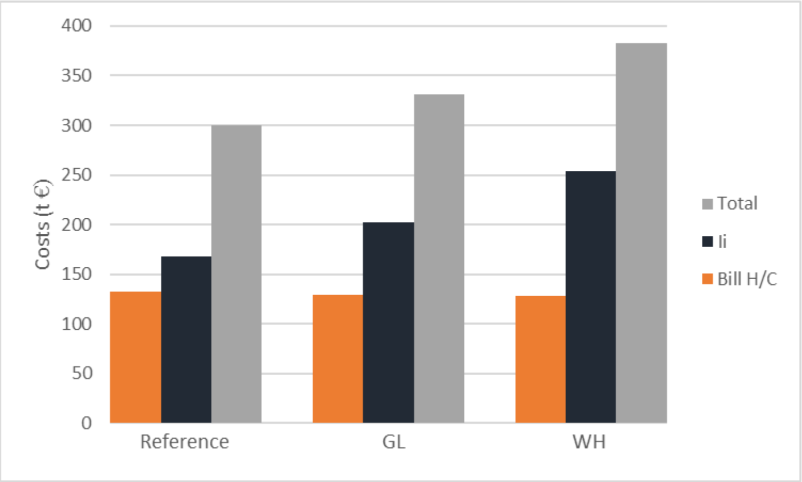

Figure 38 - Cost indicators for each climate change case over 15 years. Option 2 – fuel + electricity supply

4.7. Inter-building shading Case

Sizing and selection of installations

The sizing and selection of the installations for this case is performed by applying the same procedure as in the reference case. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 39. The absolute values of load and energy demand and the chosen installations are presented in Tables B-39 to B-42 of the Appendices.

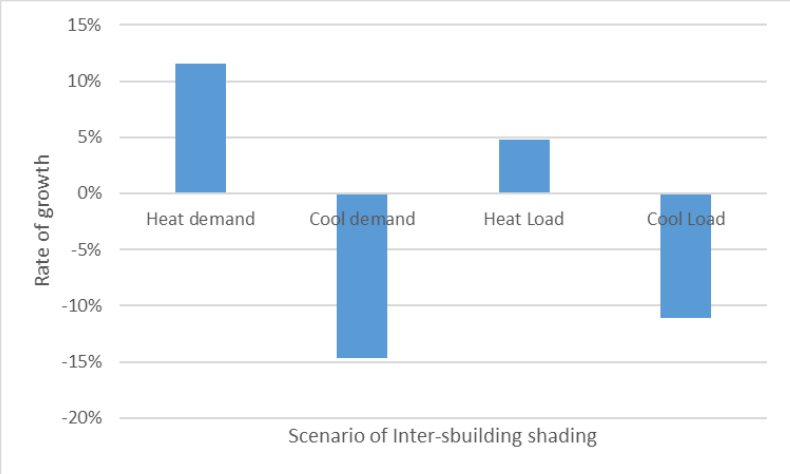

Figure 39 - Annual heat and cool demand and heat and cool load for SB case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 39. For this case, electricity consumption for lighting suffers variation from the reference. Annual energy consumption for heating, cooling and lighting for both supply energy options are depicted in Figure 40. Annual primary energy demand is presented as a sustainability indicator.

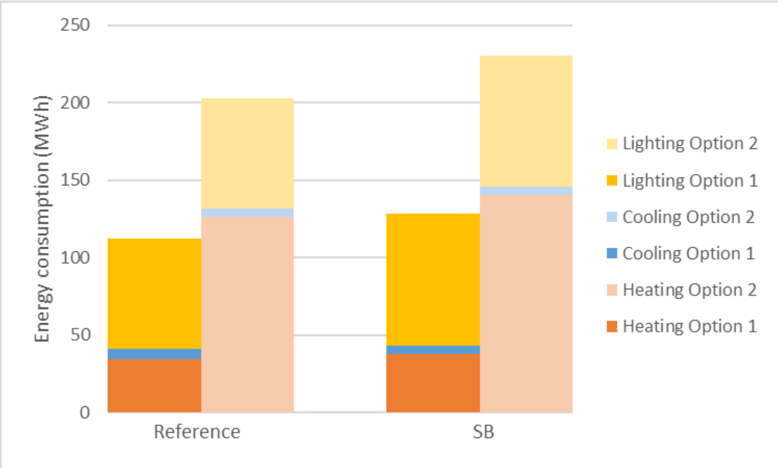

Figure 40 - Annual energy consumption for SB case and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 41 and 42, respectively.

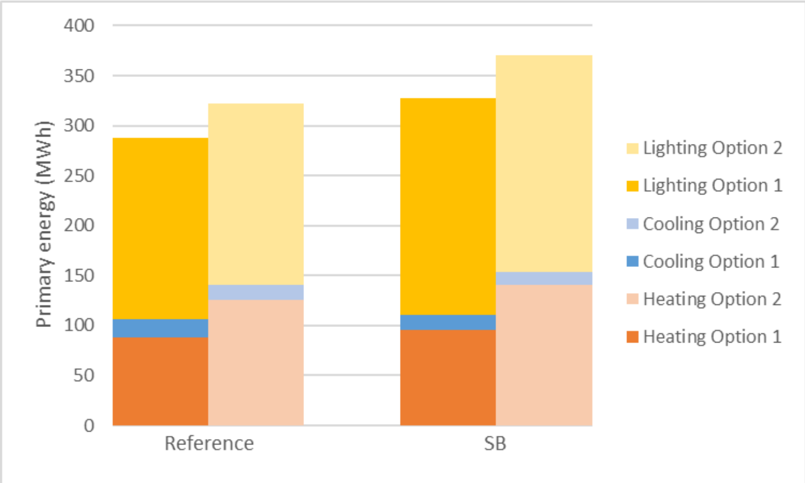

Figure 41 - Annual primary energy demand for SB case and the reference for both energy supply options

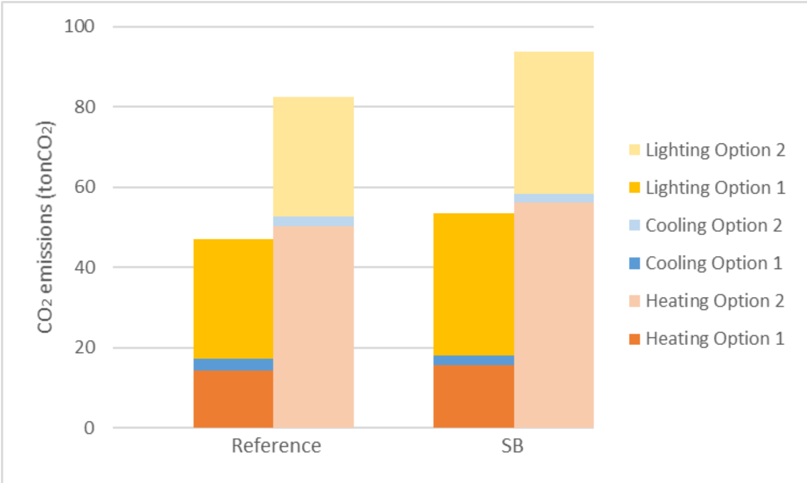

Figure 42 - Annual CO_2 emissions for SB case and the reference for both energy supply options

<u>Cost indicators</u>

Cost indicators for each climate change case, considering both supply energy options, are illustrated in Figure 43 and 44. For this type of cases, the economic performance is done in a different way – variations in investment on installations (I_i) and variations on energy bill are taken into account. Benefit, payback time and NPV cannot be calculated since inter-building shading corresponds to an external factor, thus not any measure of retrofitting or alteration to a new building project. Since investment on installations is done for each period of 15 years (lifetime of installations), annual energy bill was converted into energy bill for 15 years, in order to make indicators comparable.

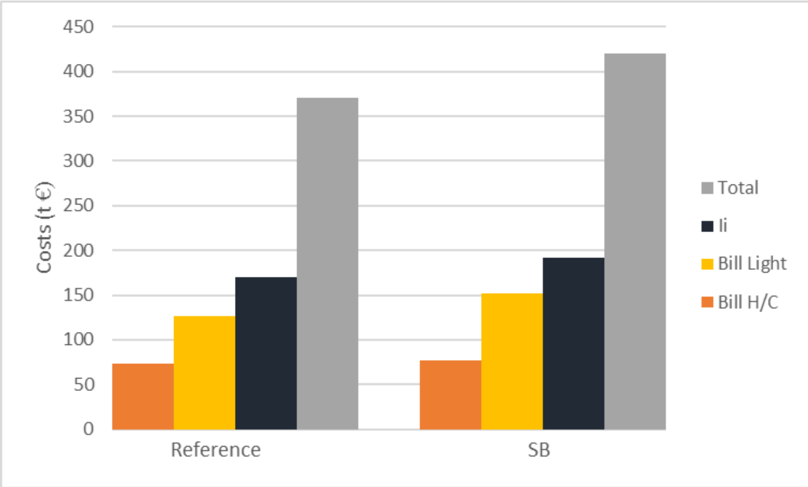

Figure 43 - Cost indicators for SB case over 15 years. Option 1 - all electric supply

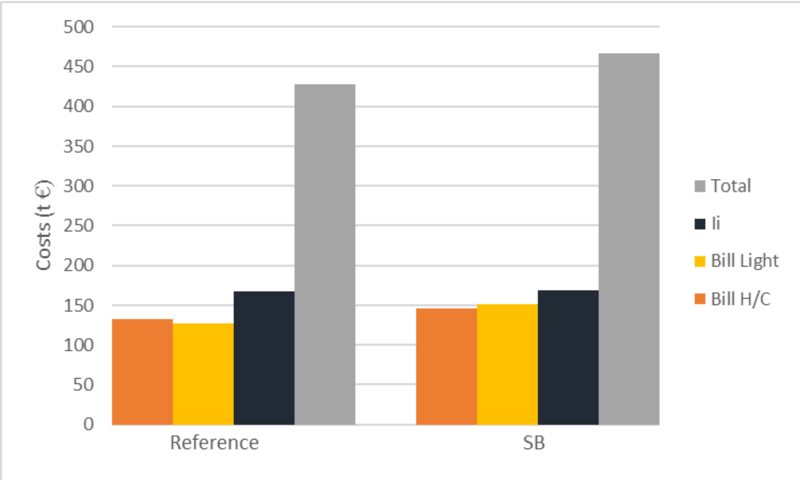

Figure 44 - Cost indicators for each SB case over 15 years. Option 2 – fuel + electricity supply

4.8. Combination Case

Sizing and selection of installations

The sizing and selection of the installations for this case is performed by applying the same procedure as in the reference case. Heating and cooling loads and annual heating and cooling energy demand variations (in comparison to the reference) are illustrated in Figure 45. The blue and the orange bars represent the isolated impact of the case of insulation I.1 and the case of glazing G.1, respectively; the grey bar represents the combined effect of the climate change case G_L and the inter-building shading case SB; the yellow bar represents the combined effect of the four cases above. The absolute values of load and energy demand and the chosen installations for this combination case are presented in Tables B-43 to B-46 of the Appendices.

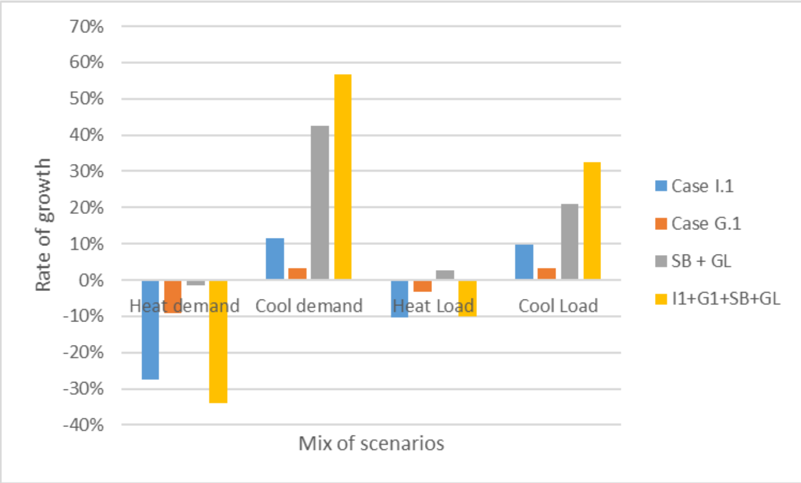

Figure 45 - Annual heat and cool demand and heat and cool load for the combination case in comparison to the reference

Energy indicators

Heating and cooling load and annual energy demand, which were used to size and select installations, are previously characterized in Figure 45. For this case, electricity consumption for lighting suffers variation from the reference. Annual energy consumption for heating, cooling and lighting for both supply energy options are depicted in Figure 46. Annual primary energy demand is presented as a sustainability indicator.

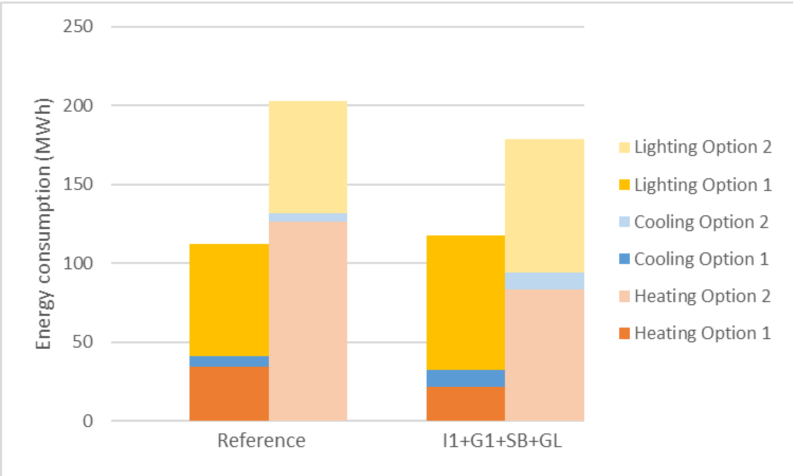

Figure 46 - Annual energy consumption for the combination case and the reference for both energy supply options

Sustainability indicators

Annual primary energy demand, which depicts the magnitude of resource depletion, and CO_2 emissions for heating and cooling are presented in Figure 47 and 48, respectively.

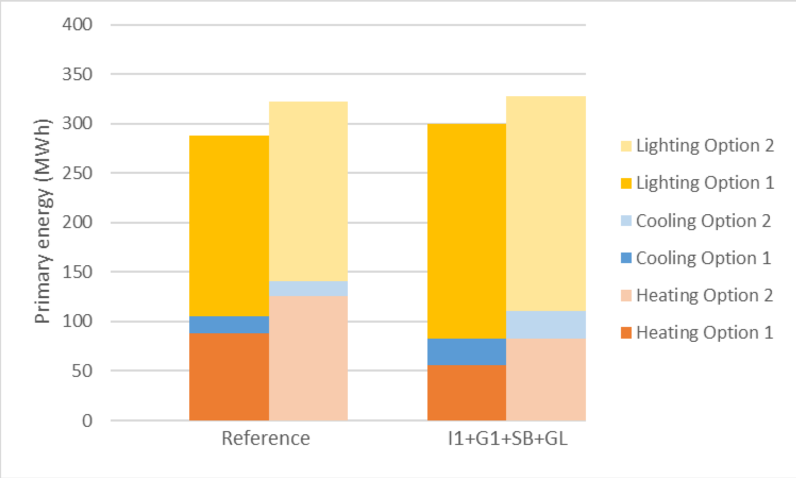

Figure 47 - Annual primary energy demand for the combination case and the reference for both energy supply options

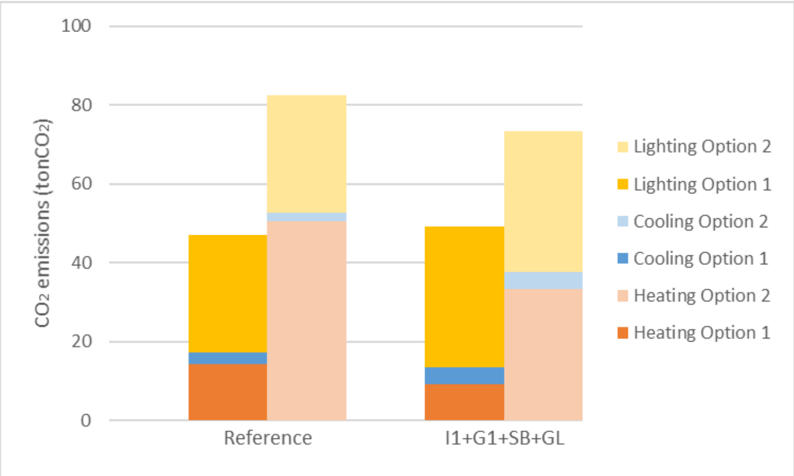

Figure 48 - Annual CO_2 emissions for the combination case and the reference for both energy supply options

Cost indicators

Cost indicators for the combination case (CC), considering both supply energy options, are illustrated in Figure 49 and 50. These indicators are calculated for the project lifetime which is considered to be, for the combination case, 75 years (lifetime of the insulation). Thus, installations are considered to be replaced every 15 years and the glazing every 30 years. ΔI_m is the difference between initial investment in insulation and glazing in CC case (Table 21) and in the reference (Table 13). For NPV calculations, a nominal annual discount rate of 3%, translated into a real discount rate of 1.3% is considered.

Table 21 - Capital investment on insulation and glazing for the combination case

Capital investment (t €)	
Insulation (Case I.1)	158
Glazing (Case G.1)	151 (every 30 years)

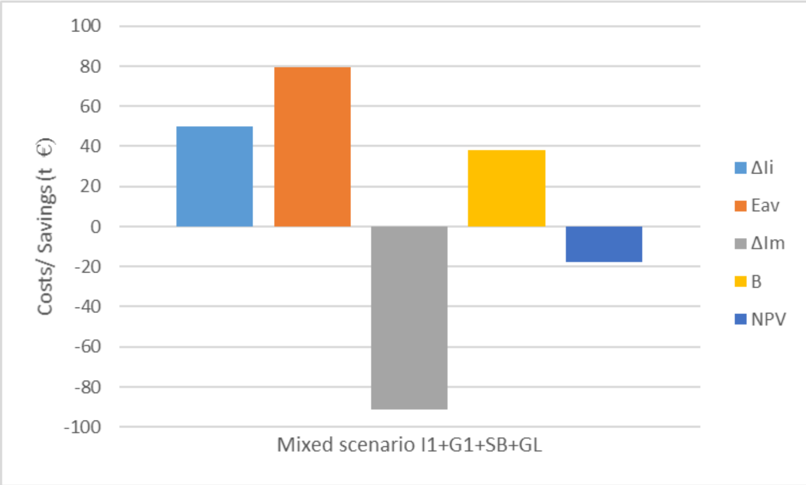

Figure 49 - Cost indicators for the combination case over the project lifetime. Option 1 - all electric supply

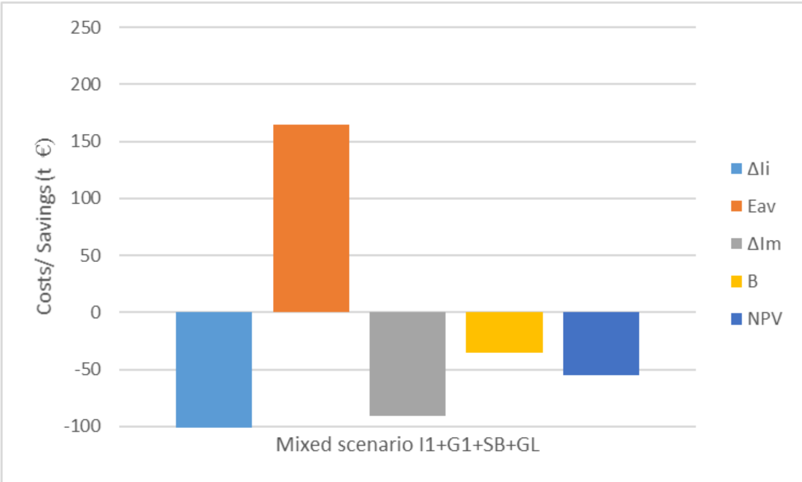

Figure 50 - Cost indicators for the combination case over the project lifetime. Option 2 – fuel + electricity supply

Simple payback for the combination case is presented in Table 22.

Table 22 - Simple payback for the combination case

Simple Payback (years)	**Supply Option 1**	**Supply Option 2**
Case CC	39	91

Chapter 5 – Discussion

The results presented in the last chapter allow to quantify the outcomes of the building concepts developed for the research project. In this chapter, considerations of the main findings are elaborated for each case in terms of energy, sustainability and cost.

5.1. Reference Case

The annual heating demand for the reference case, divided into zone heating and heating of the supply air, is estimated to be 138 MWh. This value represents around 85% percent of the energy used for providing thermal comfort, since cooling demand is only 24 MWh per year. A study on annual heating energy requirements of office buildings in a European climate [49] shows that for the Netherlands the heating degree days (HDD) are substantially higher than the cooling degree days (CDD): 2669 HDD against 70 CDD, thus making heating demand much higher than cooling demand.

The load for zone acclimatization, that determines the capacity of installations, corresponds to 278 kW for heating and 34 kW for cooling. These values represent the energy load for the 0.990th quantile, which was considered to avoid oversizing - the peak load is for heating 898 kW and for cooling 180 kW. Heating and cooling loads for installations that are used to heat or cool the supply air are 94 kW for heating and 180 kW for cooling. As a general remark, the selection method of installations usually gave preference to bigger sized installations instead of an equivalent capacity of small ones. This method allowed to optimize, in every situation, the lifetime cost (investment and energy bill) of the chosen equipment. Thus, it is natural that the selected installations for each supply option may vary from case to case.

In terms of energy consumption for the all-electric supply option, electricity consumption for lighting and office equipment is about 409 MWh, almost double of the HVAC electricity consumption of 41 MWh, with an additional 175 MWh of auxiliary equipment. A previous study [49] shows a similar share of electricity consumption: 47% consumption derived from lighting and office equipment and 24% consumption derived from the HVAC system when considering an electric powered HVAC system. For the mixed supply energy option (fuel + electricity), the HVAC electricity consumption rises to 132 MWh, with an additional 175 MWh of auxiliary equipment.

The energy consumption was translated into primary energy and CO_2 emissions for sustainability considerations. For this purpose, only the variable parameters were considered, thus office equipment consumption and emissions were disregarded. 288 MWh of primary energy were consumed for heating, cooling and lighting for the all-electric supply option (option 1), translated into 47 tons of CO_2. For the fuel and electricity supply option (option 2), these values are higher: 322 MWh and 82 tons of CO_2. Even though energy consumption is 81% higher for option 2 than for option 1, there is a smaller increase on primary energy consumption of 11% and on CO_2 emissions of 74% in option 2 in relation to option 1. This is due to the facts that the primary energy factor of natural gas is 1 (since it is a raw fuel) while the primary energy factor of electricity is 2.56 and that natural gas is a cleaner source than the mix of resources that are used to produce the electricity consumed.

Energy bill differs between supply options only in heating, which is 4 thousand euros for 34 MWh of electricity consumed for option 1 and 8 thousand euros for 126 MWh of natural gas consumed for option 2. This fact allows to observe that the cost of the natural gas is substantially lower than the cost of electricity. Investment on installations between supply options is practically the same.

5.2. Insulation Cases

When applying increasing levels of insulation, the overall U-value of the building decreases, which means that the thermal resistance of the building increases. Thus, there is a reduction of heat exchange with the environment. The overall U-value for the reference case is 0.62 W/(m^2.K), while for case I.1 is 0.49 W/(m^2.K), for case I.2 is 0.46 W/(m^2.K) and for case I.3 is 0.44 W/(m^2.K).

By evaluating these data, heating demand is expected to decrease and cooling demand to increase, since in winter more heat remains in the building and also in the summer, when solar heat gains are substantial. A previous study about the effect of materials façade on the energy efficiency of office buildings [50] revealed that with decreasing average U-value, a large reduction in heating demand and a slight grow in cooling demand were observed. In fact, for the developed cases heating demand reduces between 27% and 38%, having a high impact on energy savings since it represented 85% of energy demand for acclimatization in the reference. Cooling demand grows between 11% and 19%, having a lower impact on energy consumption since it represented only 15% of the energy demand for HVAC in the reference. Heat and cool loads follow the trend of the respective heating and cooling demand in a shorter extent – heat load decreases between 10% and 15% while cool load increases between 10% and 14%.

Translated into energy consumption for HVAC, there is an overall decrease for both supply options. In option 1, there is a reduction between 22% and 32% on energy consumption. In option 2, a higher reduction between 27% and 34% and higher absolute energy savings are observed, since heating with fuel is performed with a lower efficiency.

In terms of primary energy demand and CO_2 emissions, the previous perceived trends (for energy consumption) are also verified. There is however, a narrower gap of primary energy demand between supply options, since natural gas used in option 2 is considered a primary resource.

Cost-wise, for supply option 1, there is about 100 thousand € of savings due to lower capacity of installations over the 75 years of the project for all the insulation cases. Energy savings increase with increasing level of insulation, but investment on insulation increases in a higher magnitude. Due to this, benefit and NPV decreases with higher insulation; NPV is even negative for I.3 case. For supply option 2, an additional 35 thousand € investment on installations is verified – savings in heating capacity are offset by more spending in cooling capacity. Energy savings are higher than in supply option 1, but increasing investment on installations are responsible for lower benefit and NPV.

The ultimate goal of these analyses is to support building owners with the decision of whether or not to invest in a solution based on their expectations: a preference for energy, sustainability or cost or a compromise between them. If the decision is based on energy and sustainability, the case that grants higher energy savings and lower primary energy demand and CO_2 emissions in a building with an all-electric HVAC system is I.3 case. If the aim is focused on cost-effectiveness, I.1 is the best case. The same conclusions can be drawn for a mixed energy supply HVAC system.

5.3. Glazing Cases

The glazing thermal performance variation was evaluated through its U-value. Other factors could be used to analyze its performance, such as the g-value, but a surprising difficulty on creating a glazing inventory due to lack of data provided by manufacturers limited the research. Thus, the different glazing studied differ mainly in their U-value, while their g-value and solar transmittance slightly differs. The same process as for insulation applies: with decreasing U-value of glazing solutions, the overall U-value of the building decreases, which means that the thermal resistance of the building increases. Thus, there is a reduction of heat exchange with the environment. The overall U-value for the reference case is 0.62 W/(m^2.K), while for case G.1 is 0.55 W/(m^2.K) and for case G.2 is 0.48 W/(m^2.K). Shading devices were left out of the report, since cooling demand is a very small fraction of the energy demand.

As with insulation cases, the decrease of the average U-value of the building in glazing cases translated into a large reduction in heating demand and a slight grow in cooling demand. Heating demand decreased between 9% and 20% while cooling demand increased between 3% and 13%. Heat and cool loads follow the trend of the respective heating and cooling demand in a shorter extent – heat load decreases between 3% and 7% while cool load increases between 3% and 10%.

When observing the energy consumption for HVAC, there is an overall decrease for both supply options. In option 1, there is a reduction between 12% and 20% on energy consumption. In option 2, a lower reduction between 8% and 18% but higher absolute energy savings are observed, since heating with fuel is performed with a lower efficiency.

In terms of primary energy demand and CO_2 emissions, the previous perceived trends (for energy consumption) are also verified. Again, a narrower gap of primary energy demand between supply options is observable, since natural gas used in option 2 is considered a primary resource.

When analyzing cost indicators, for supply option 1, it can be seen that there is about 5 thousand € of additional investment on installations over the 75 years of the project for both glazing cases. This small difference in relation to the reference is due to the different installations chosen in order to optimize their lifetime cost – a compromise between investment and energy bill. Energy savings increase with increasingly lower U-value glazing, but investment on glazing increases in a higher magnitude. Due to this, benefit and NPV decrease. For supply option 2, an additional investment on installations between 8 and 17 thousand € is verified – this is also due to lifetime cost of installations optimization, which leads to a higher investment but a lower energy bill. For both supply options, both G.1 and G.2 cases have a negative NPV (even though case G.1 verifies a positive benefit); G.2 case has a more negative NPV since investment on glazing is higher than energy savings.

For investment purposes, if the decision is based on energy and sustainability, the case that grants higher energy savings and lower primary energy demand and CO_2 emissions in a building with an all-electric HVAC system is G.2 case. If the aim is focused on cost-effectiveness, neither case is cost-effective, but case G.1 presents a closer to 0 NPV (-4 thousand €). If the value of money over time is not accounted for, case G.1 has a positive benefit and its payback time is lower than the lifetime of the project. The same conclusions can be drawn for a mixed energy supply HVAC system.

5.4. Renewable Energy Cases

Several wind turbines and PV systems for electricity production were studied in order to select the alternative with the lowest investment and cost of energy production.

The chosen small wind turbine has an investment cost of 3,110 €/kW and an electricity production cost of 0.22 €/kWh. According to a study on renewable power generation costs [51], the average cost of new wind farms in the Netherlands in 2014 was 1,928 €/kW. The investment cost on small wind turbines is understandably higher due to their lower capacity and the fact that these turbines are not integrated in a wind farm. The same study points for an average production cost from wind resource of 0.08 €/kWh in Europe. This value is substantially lower than the obtained in the project (0.22 €/kWh), since the location of implementation has the lowest average wind speed category of the Netherlands (3.5 to 4 m/s [52]) and the higher investment. A sensitivity analysis was performed, with a weather station in a coastal location of the country, which resulted in a cost of electricity of 0.09 €/kWh.

The chosen PV system has an investment cost of 2.1 €/W_p and an electricity production cost of 0.134 €/kWh. The same report of renewable power generation costs indicates an investment cost for Europe ranging between 1.3 €/W_p and 3.7 €/W_p. The electricity production cost varies between 0.14 €/kWh and 0.15 €/kWh for the Netherlands [53], a similar value to the one of the project.

In terms of energy production, the PV system produces annually around 30 MWh of electricity while the small wind turbines only produce around 10 MWh. Thus, the PV system has more potential of primary energy savings and CO_2 emissions reduction.

Both renewable energy technologies are not cost-effective with the net-metering policy in place, since the electricity production cost for both is higher than the price of the grid electricity (0.12 €/kWh). Thus, benefit and NPV for these technologies are negative. However, if considering residential electricity price (0.22 €/kWh), PV systems are highly profitable while small wind turbines are narrowly profitable (since the wind resource at the location is low).

For investment purposes, if the decision is based on energy and sustainability, PV systems should be installed since they allow substantial energy savings and the building is consuming zero-emission electricity. However, if the decision is financial, there is no reason to invest in these technologies. In order to revert this situation and attract building owners to invest in renewable energies, government policies should be in practice.

5.5. Structural Cases

The variation of the WWR of a building has influence on the average U-value of the building but also on the solar heat gains that pass through the windows. Windows normally have a higher U-value than the exterior walls, which means that the higher the WWR, the higher the average U-value of the façade; thus, the building has a lower thermal resistance. However, a higher WWR results in an increase in solar heat gains, which balances or even offsets the previous effect.

In the W20 case, where the reference ‘s WWR was set to half (20%), heat demand increased by 10%, while cool demand decreased by 37%. From these values, it can be concluded that solar heat gain variations influence more the building’s thermal behavior than U-value variations, since a lower U-value would have a lower heating demand and a higher cooling demand. Heat and cool loads follow the trend of the respective heating and cooling demand in a shorter extent – heat load increases by 3% while cool load decreases by 14%. For the W80 case, where the reference ‘s WWR was set to double (80%), heat demand decreased by 9%, while cool demand increased by 180%. In this case, heat and cool loads also follow the trend of the respective heating and cooling demand in a shorter extent – heat load decreases by 2% while cool load increases by 71%. These results show that cooling demand is more sensible to WWR variations, where solar heat gains play an important role.

In terms of energy, W80 corresponds to the case with higher energy consumption for HVAC in both supply options. However, when electricity consumption for lighting is considered, W80 is the case with the lowest energy consumption. This is due to the fact that a higher WWR results in more daylight availability, thus a lower need for artificial lighting. The same conclusions follow for primary energy demand and CO_2 emissions.

For these type of cases, cost calculations were developed in a different manner, since benefit and NPV cannot be calculated for reasons previously explained. A total cost was instead calculated, taken into consideration the following variables: heating and cooling energy bill, lighting electricity bill and investment on installations. For both supply options, energy bill for heating and cooling and investment on installations are lowest for the reference and highest for the W80 case. However, lighting electricity consumption is the lowest for W80 case (highest WWR) and highest for W20 case (lowest WWR). Given this, for supply option 1, total costs are the minimum for W80 case. Surprisingly, for supply option 2, total costs are maximum for the same case (W80) and minimum for the reference. This discrepancy is due to a much higher investment on installations for supply option 2 in W80 case, which offsets its lighting electricity savings.

When opting for the WWR in the design of this project, if energy and sustainability are key factors, a higher WWR than the reference (41%) is preferable, since it leads to lower energy consumption taking into consideration HVAC + lighting. When cost is a key factor, an all-electric HVAC system building optimizes its costs for a higher WWR while a mixed-fueled HVAC system building optimizes its costs for an average WWR of 41%.

5.6. Climate Change Cases

Energy demand for heating is expected to decrease with climate change, but researchers suggest that cooling demand is more sensitive to climate change [9], which is expected to increase in a higher degree. Results of climate change cases corroborate these findings – while heating demand decreases by 11% on the optimistic case of climate change and by 25% on the pessimistic case, cooling demand increases by 64% on the optimistic case and 200% on the pessimistic one. Heat and cool load go along with the trends of heating and cooling demand – heat load slightly decreases between 2% and 5% and cool load increases between 35% and 84%.

These variations cause, for supply option 1, an overall increase on energy consumption for both climate change cases. However, for supply option 2, the inverse is verified –even though heating decreases in a lower proportion than cooling increases, heating corresponds to 95% of HVAC energy consumption, thus the total energy consumption decreases overall.

Primary energy demand for climate change cases is higher for both supply options, despite the lower energy consumption verified in option 2. CO_2 emissions verify the same behavior as energy consumption.

Energy and sustainability wise, if the moderate scenario is considered, no significant variations in energy consumption and emissions are expected but cooling demand will represent a higher share of the energy demand of the HVAC system.

Cost-wise, energy bill is expected to increase between 1% and 15% for supply option 1 and to decrease between 3% and 4% for supply option 2. In terms of investment on installations, costs are expected to increase between 6% and 11% for supply option 1 and between 21% and 52% for supply option 2. Thus, total costs are expected to increase by a considerable amount due to climate change.

Given these considerations, climate change cannot be ignored: cooling demand will represent a higher share, which can justify solar control solutions; the capacity of installations for future weather may be insufficient to supply the acclimatization needs, and additional investment costs can rise up to 50% for the most extreme scenario.

5.7. Inter-building shading Case

The presence of buildings in the surroundings influences the solar heat gains that reach the building and the daylight availability in the interior. From empirical experience, it is logical that with lower solar heat gains, heating demand will increase in winter and cooling demand will decrease in summer. Daylight availability should be lower, implying the need for additional artificial lighting.

Heating demand increased by 12%, with heat load increasing 5%. Cooling demand decreased by 15%, with cool load decreasing 11%.

Overall energy consumption for the HVAC system increased by 5% for supply option 1 and by 10% for supply option 2. While energy consumption for acclimatization does not suffer significant variations, electricity consumption for lighting increases by 20%. This results in a higher energy consumption of 14% for each of the supply option considered.

Primary energy demand and CO_2 emissions, when considering shading from surrounding buildings, increases by approximately between 13% and 15% depending on the selected supply option.

Investment on installations follows the same trend as energy bill for heating, cooling and lighting, causing an increase in overall costs of 13% for supply option 1 and 10% for supply option 2.

For this specific case, where surrounding buildings - same height of the reference building at a distance of 25 m from it - induce shading on the reference, energy, emissions and costs slightly increase between 10% and 15%. Nonetheless, it is important to take into account the effect that the surroundings have on the projected buildings, especially in denser urban environments.

5.8. Combination Case

Combining the case of insulation I.1 with the case of insulation G.1, which were the most profitable solutions of insulation and glazing, the average U-value of the building decreases from 0.62 W/(m^2.K) to 0.42 W/(m^2.K), thus the building increases its thermal resistance. With the addition of climate change and inter-building shading effects, the decrease in heating demand (verified in I.1 + G.1 cases) is slightly amplified and the increase in cooling demand is severely amplified. The heating demand is predicted to decrease by 34% while the cooling demand is predicted to increase by 57%. Heat load should decrease by 10% while cool load should increase by 32%.

This results in an energy consumption for HVAC that is 20% lower for supply option 1 and 30% lower for supply option 2, since heating represents a much higher share than cooling in the overall energy demand. However, due to surrounding shading, electricity consumption for lighting increases 20%. With lighting consumption included, total energy consumption rises by 5% considering supply option 1 and declines by only 12% considering supply option 2.

Primary energy demand increases by 4% for supply option 1. For supply option 2, even though energy consumption decreases, primary energy demand increases by 2%, since the electricity share (with a PE factor of 2.56) is higher than the fuel share (with a PE factor of 1) of the total demand. CO_2 emissions verify the same behavior as energy consumption even for supply option 2 since the emission factors for electricity and natural gas are similar (0.419 $kgCO_2$/kWh for electricity and 0.400 $kgCO_2$/kWh for natural gas).

In terms of costs, for supply option 1 and considering HVAC energy demand, investment on installations is 50 thousand € lower than in the reference for the 75 years of project lifetime. Energy consumption accounts for another 80 thousand € of savings. But a high investment on glazing and insulation (91 thousand € of additional cost) implies a lower benefit (38 thousand €) and a negative NPV. For supply option 2, however, benefit is negative (and consequently the NPV) despite more energy savings. While option 1 verifies savings on investment on installations, option 2 verifies an additional investment of 100 thousand €. The explanation for this is that in option 1, heating and cooling is done with the same device; heating load is much higher than cooling load; when cooling load drastically increases due to climate change, heat load is still higher; thus the increase of cool load does not alter the number of AC devices. In option 2 however, heating and cooling are done separately; thus, when cool load increases, the number of AC devices that provide cooling also increase.

This combination case was performed in order to determine onto what extent would external factors affect the outcome of building solutions applied to reduce energy consumption. HVAC energy savings of around 35% for both supply options for insulation and glazing with better performance translated into only 20% savings for supply option 1 and 30% savings for supply option 2 when considering external factors. These values are even lower when considering additional lighting electricity consumption due to shading. Both measures of insulation and glazing presented positive benefit but when considering external factors benefit decreased or even became negative. Given this, external factors cannot be ignored when considering investment on building solutions.

Chapter 6 – Conclusions and future developments

The aim of the research project was to analyze different building concepts in terms of geometry, materials and technologies in order to evaluate their impact on energy consumption, on the capacity of installations and on the cost of energy and installations. These outputs were translated into performance indicators of energy, sustainability and costs that allow users (or clients) to make a conscious decision based on their motivations. Additionally, the influence of external factors on the building's thermal performance was measured.

Several sub questions were formulated in order to develop a method that would support the search for an answer to the research question. The main issues to be studied were the type of building concepts, the indicators of energy, sustainability and cost that would be used to analyze these concepts, the identification of the external factors that play a role in the building thermal performance and the way of measuring them and the selection process of installations.

The building concepts developed for the research project and derived from a reference case included varying materials – different thicknesses of insulation, glazing with different thermal properties – varying façade structures – different window-to-wall ratios – and the implementation of renewable energy technologies – small wind turbines and PV systems. For each case, a selection method for installations was applied, in order to guarantee the application of the installations with the lowest lifetime cost. Additionally, for each case two supply options for HVAC energy demand were considered: all-electric supply or fuel (natural gas) and electricity supply.

Furthermore, the effects of external factors were assessed in isolation. Finally, a combination of material solutions with external factors was studied with the aim of determining to what extent external factors influence the outcomes obtained for the building concepts.

The results obtained from the defined building concepts answer the research question for the specific reference building but also identify general trends in terms of impacts of solutions on building performance.

Another goal parallel to the research was to study a new building simulation tool that could be used for further projects in the company Witteveen+Bos. The simulation tool proved to be very flexible, allowing the conception of several building concepts where different materials, geometries, renewable energy technologies and installations could be applied. A database was created with all the implemented solutions, thus allowing this information to be used in future projects. Furthermore, the tool has a user friendly interface that does not require extensive training and which main highlight is its transparency, since every underlying equation and variable that makes part of the model can be inspected. A distinct key functionality lies on the fact that the software can be expanded with new modelling capabilities, allowing the users to adapt the tool according to their needs.

Future work includes the expansion of the simulation program, since most of the cost analysis was performed in another tool due to its limitations; the development and actualization of the database, that includes more materials and technologies with updated characteristics and prices; exploring other parameters of energy and sustainability, since only a small sample of a vast range of indicators was used; the study of unconventional technologies and materials, such as phase-change materials that take advantage of the dynamic profile of heat exchange.

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Appendices

A: Inventory of materials and installations

Table A- 1 Summary table of the adopted insulation properties. Source: [54].

Insulation							
Material	**Size (m2)**	**Thickness (m)**	**Thermal conductivity (W/(m.K))**	**Density (kg/m^3)**	**Specific heat (J/(kg.K))**	**Price per unit area (Eur/m^2)**	**Structure**
Kooltherm K15	0.72	0.02	0.021	35	1,470	14.65	External Wall
		0.06	0.020			24.95	
		0.08				30.10	
		0.12				37.70	
Kooltherm K7	1.20	0.04	0.021	35	1,470	17.95	Sloped Roof
		0.08	0.020			29.30	
		0.12				40.30	
Kooltherm K3 (K10)	0.72	0.02	0.021	35	1,470	9.50	Internal Floor (Ceiling)
		0.06	0.020			18.90	
		0.08				23.25	
		0.16				45.80	
Therma TF70	0.72	0.03	0.023	30	1,470	12.60	External Floor
		0.05				17.95	
		0.08				28.35	
		0.10				33.40	

Table A- 2 - Summary table of the adopted glazing properties. Source: [55][56].

Glazing							
Model	**U-value ($W/(m^2.K)$)**	**g-value**	**Solar Transmittance**	**External reflection**	**Emissivity (ext/int)**	**Price (€/m²)**	**Manufacturer**
CLIMAPLUS ONE air ground floor	1.50	0.51	0.45	0.38	0.11/0.06	89.54	Saint-Gobain Glass
other floors						113.74	
CLIMAPLUS ONE ground floor	1.10	0.51	0.45	0.38	0.11/0.06	96.80	
other floors						121.00	
CLIMATOP XN ground floor	0.70	0.53	0.47	0.31	0.14/0.05	127.05	
other floors						151.25	

Table A- 3 - Technical characteristics of the tubular lamp used to provide artificial light. Source: [57].

Product description	Nominal wattage (W)	Color rendering index (Ra)	Luminous flux (lm)
DALI 80 W 4000 K	80	> 80	8,000

Table A- 4 - Sample database of air conditioning devices. Source: Physical catalogues.

	Air conditioning							
	Model	**Heating Capacity (kW)**	**COP**	**Cooling Capacity (kW)**	**EER**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
Ceiling Un.	**PSH-S35i**	4.1	4.1	3.6	5.9	3,090	15	Mitsubishi Electric
	PSH-S50i	5.5	4.0	5.0	5.7	3,495		
	PSH-S60i	6.9	4.0	5.7	6.0	3,865		
	PSH-S71i	7.9	4.0	7.1	6.0	4,605		
	PSH-P100i	11.2	3.8	9.4	5.1	6,070		
	PSH-P125i	14.0	3.7	12.3	3.5	6,850		
	PSH-P140i	16.0	3.5	13.6	3.2	7,950		
Floor Un.	**VSH-ZRP71i**	7.6	4.0	7.1	6.3	5,630		
	VSH-ZRP100i	11.2	4.0	10.0	5.5	7,170		
	VSH-ZRP125i	14.0	4.0	12.5	4.9	7,830		
	VSH-ZRP140i	16.0	4.4	13.4	5.3	8,890		
Ceiling Un.	**FCQG71F**	7.5	4.0	6.8	3.4	4,084	15	Daikin
	FCQG100F	10.8	4.2	9.5	3.9	5,249		
	FCQG125F	13.5	3.6	12.0	3.7	5,945		
	FCQG140F	15.5	3.6	13.4	3.2	6,603		

Table A- 5 - Sample database of chillers/heat pumps. Source: Physical catalogues.

	Chillers/Heat pumps							
	Model	**Heating Capacity (kW)**	**COP**	**Cooling Capacity (kW)**	**EER**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
air condensation	**EWAQ016BAWP**	-	-	16.6	2.9	9,144	15	Daikin
	EWAQ021BAWP	-	-	20.7	2.7	10,629		
	EWAQ025BAWP	-	-	24.7	2.5	11,887		
	EWAQ032BAWP	-	-	30.9	2.3	13,848		
	EWAQ040BAWP	-	-	41.5	2.7	18,112		
	EWYQ016BAWP	17.0	3.0	16.6	2.9	10,400		
	EWYQ021BAWP	21.3	2.9	20.7	2.7	12,108		
	EWYQ025BAWP	25.7	2.8	24.7	2.5	13,558		
	EWYQ032BAWP	32.1	2.9	30.9	2.3	15,774		
	EWYQ040BAWP	42.5	2.9	41.5	2.7	20,657		
water condens.	**EWWP022KBW1N**	27.5	4.5	21.4	3.5	6,215		
	EWWP045KBW1N	55.0	4.5	42.8	3.5	10,350		
	EWWP090KBW1N	110.0	4.6	85.7	3.5	14,239		
	EWWP120KBW1N	155.0	4.6	121.0	3.6	18,603		
	EWWP185KBW1N	237.0	4.6	185.0	3.6	27,388		

Table A- 6 - Sample database of boilers. Source: Physical catalogues: Daikin; [58]: Buderus

Boilers					
Model	**Heating Capacity (kW)**	**Efficiency**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
EKOMBG22A	22.7	1.07	2,426	15	Daikin
EKOMBG28A	28.4	1.07	2,668		
EKOMBG33A	32.1	1.09	2,850		
Logano plus GB312	90	1.09	10,926	15	Buderus
Logano plus GB312	120	1.09	11,065		
Logano plus GB312	160	1.09	12,138		
Logano plus GB312	200	1.09	13,536		
Logano plus GB312	240	1.09	15,736		

Table A- 7 - Sample database of water radiators. Source: [59].

Water Radiators				
Model	**Heating capacity (kW)**	**Price (€)**	**Lifetime (years)**	**Manufacturer**
REH 0.8 635 x 834mm	0.80	897	15	Hudson Reed
REH 1.7 472mm x 1600mm	1.75	798		
REV 2.6 1600mm x 590mm	2.60	925		
REH 3.2 635mm x 1647mm	3.18	998		
REV 3.7 1780mm x 590mm	3.70	1,168		

B: Energy demand, load and size of installations of case studies

Table B- 1 – Selection method of installations that provide heating and cooling for the reference case in which supply energy is all electric. In blue, the number of air conditioning devices installed - as the same device is used to provide both heat and cold, the number of devices chosen depends on the highest number needed for heating or cooling. Light yellow corresponds to the selected solution

Reference - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	**Nr Heating units**	**Nr Cooling Units**	**Invest Equip (t €)**	**Elec heating (MWh)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
PSH-S35i	72	12	222	15.5	1.6	2.0	253
PSH-S50i	54	12	189	15.9	1.7	2.1	220
PSH-S60i	42	6	162	15.9	1.6	2.1	194
PSH-S71i	36	6	166	15.9	1.6	2.1	197
PSH-P100i	30	6	182	16.7	1.9	2.2	215
PSH-P125i	24	6	164	17.2	2.7	2.4	200
PSH-P140i	18	6	143	18.1	3.0	2.5	181
AHU heating and cooling							
EWWP022	4	9	56	16.4	4.1	2.4	93
EWWP045	2	5	52	16.4	4.1	2.4	88
EWWP090	1	3	43	16.2	4.0	2.4	79
EWWP120	1	2	37	16.2	4.0	2.4	73
EWWP185	1	1	27	16.2	4.0	2.4	63

Table B- 2 – Selection method of installations that provide heating and cooling for the reference case in which supply energy is both fuel and electricity. The same boiler can be used in both zone heating and supply air heating, thus the number of boilers needed is not rounded. Light yellow corresponds to the selected solution.

Reference – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	**Nr Boilers**	**Nr Radiators**	**Invest Equip (t €)**	**Fuel heating (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
GB312-160+REV2.6	1.74	108	124	58.3	3.8	181
GB312-200+REV3.2	1.39	90	117	58.3	3.8	174
GB312-240+REV3.7	1.16	78	123	58.3	3.8	179
Zone cooling						
Model	**Nr Cooling Units**		**Invest Equip (t €)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
PSH-S35i	12		37	1.6	0.2	40
PSH-S50i	12		42	1.7	0.2	45
PSH-S60i	6		23	1.6	0.2	26
PSH-S71i	6		28	1.6	0.2	30
PSH-P100i	6		36	1.9	0.2	40
PSH-P125i	6		41	2.7	0.3	46
PSH-P140i	6		48	3.0	0.4	53
AHU heating						
Model	**Nr Boilers**		**Invest Equip (t €)**	**Fuel heating (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
GB312-160	0.59		12	67.8	4.4	78
GB312-200	0.47		0	67.8	4.4	66
GB312-240	0.39		0	67.8	4.4	66
AHU cooling						
Model	**Nr Cooling Units**		**Invest Equip (t €)**	**Elec cooling (MWh)**	**Annual En cost (t €)**	**Lifetime cost (t €)**
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.0	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 3 - Heating and cooling load for zone acclimatization and ventilation for case I.1

Load (kW)	
Zone Heating	717
ZH 0.990th quantile	249
AHU heating	85
Zone Cooling	239
ZC 0.990th quantile	55
AHU cooling	181

Table B- 4 - Heating and cooling yearly energy demand for case I.1

Energy demand (MWh)	
Zone Heating	38
Zone Cooling	12
AHU heating	61
AHU cooling	14
Total Heating	99
Total Cooling	26

Table B- 5: Selection method of installations that provide heating and cooling for case I.1 in which supply energy is all electric.

Case I.1 - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	18	204	9.4	2.1	1.4	224
PSH-S50i	48	12	168	9.6	2.1	1.4	189
PSH-S60i	42	12	162	9.6	2.0	1.4	183
PSH-S71i	36	12	166	9.6	2.0	1.4	187
PSH-P100i	24	6	146	10.1	2.4	1.5	168
PSH-P125i	18	6	123	10.4	3.5	1.7	148
PSH-P140i	18	6	143	11.0	3.8	1.8	169
AHU heating and cooling							
EWWP022	4	9	56	13.7	4.1	2114	88
EWWP045	2	5	52	13.6	4.1	2104	83
EWWP090	1	3	43	13.5	4.1	2086	74
EWWP120	1	2	37	13.4	4.0	2079	68
EWWP185	1	1	27	13.4	4.0	2079	59

Table B- 6 - Selection method of installations that provide heating and cooling for case I.1 in which supply energy is both fuel and electricity.

Case I.1 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.56	96	113	35.2	2.3	147
GB312-200+REV3.2	1.25	84	111	35.2	2.3	145
GB312-240+REV3.7	1.04	72	116	35.2	2.3	150
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	18		56	2.1	0.2	59
PSH-S50i	12		42	2.1	0.3	46
PSH-S60i	12		46	2.0	0.2	50
PSH-S71i	12		55	2.0	0.2	59
PSH-P100i	6		36	2.4	0.3	41
PSH-P125i	6		41	3.5	0.4	47
PSH-P140i	6		48	3.8	0.5	55
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime Cost (t €)
Log plus GB312-160	0.53		12	56.2	3.7	67
Log plus GB312-200	0.43		0	56.2	3.7	55
Log plus GB312-240	0.35		0	56.2	3.7	55
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.1	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 7 - Heating and cooling load for zone acclimatization and ventilation for case I.2

Load (kW)	
Zone Heating	657
ZH 0.990th quantile	241
AHU heating	86
Zone Cooling	242
ZC 0.990th quantile	59
AHU cooling	180

Table B- 8 - Heating and cooling yearly energy demand for case I.2

Energy demand (MWh)	
Zone Heating	34
Zone Cooling	13
AHU heating	59
AHU cooling	14
Total Heating	93
Total Cooling	27

Table B- 9 - Selection method of installations that provide heating and cooling for case I.2 in which supply energy is all electric.

Case I.2 - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	60	18	185	8.4	2.2	1.3	204
PSH-S50i	48	12	168	8.6	2.3	1.3	187
PSH-S60i	36	12	139	8.6	2.2	1.3	158
PSH-S71i	36	12	166	8.6	2.2	1.3	185
PSH-P100i	24	12	146	9.1	2.6	1.4	166
PSH-P125i	18	6	123	9.3	3.7	1.6	147
PSH-P140i	18	6	143	9.8	4.1	1.7	168
AHU heating and cooling							
EWWP022	4	9	56	13.1	4.1	2.1	87
EWWP045	2	5	52	13.1	4.1	2.0	82
EWWP090	1	3	43	13.0	4.1	2.0	73
EWWP120	1	2	37	12.9	4.0	2.0	67
EWWP185	1	1	27	12.9	4.0	2.0	58

Table B- 10 - Selection method of installations that provide heating and cooling for case I.2 in which supply energy is both fuel and electricity.

Case I.2 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.50	96	113	31.6	2.1	144
GB312-200+REV3.2	1.20	78	105	31.6	2.1	136
GB312-240+REV3.7	1.00	66	109	31.6	2.1	139
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	18		56	2.2	0.3	60
PSH-S50i	12		42	2.3	0.3	46
PSH-S60i	12		46	2.2	0.3	50
PSH-S71i	12		55	2.2	0.3	59
PSH-P100i	12		73	2.6	0.3	77
PSH-P125i	6		41	3.7	0.4	48
PSH-P140i	6		48	4.1	0.5	55
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.54		12	54.1	3.5	65
GB312-200	0.43		0	54.1	3.5	53
GB312-240	0.36		0	54.1	3.5	53
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.1	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 11 - Heating and cooling load for zone acclimatization and ventilation for case I.3

Load (kW)	
Zone Heating	614
ZH 0.990th quantile	235
AHU heating	83
Zone Cooling	245
ZC 0.990th quantile	63
AHU cooling	181

Table B- 12 - Heating and cooling yearly energy demand for case I.3

Energy demand (MWh)	
Zone Heating	30
Zone Cooling	14
AHU heating	56
AHU cooling	14
Total Heating	86
Total Cooling	28

Table B- 13 - Selection method of installations that provide heating and cooling for case I.3 in which supply energy is all electric.

Case I.3 – Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	60	18	185	7.2	2.4	1.1	203
PSH-S50i	48	18	168	7.4	2.5	1.2	185
PSH-S60i	36	12	139	7.4	2.3	1.2	157
PSH-S71i	30	12	138	7.4	2.3	1.2	156
PSH-P100i	24	12	146	7.8	2.7	1.3	165
PSH-P125i	18	6	123	8.0	4.0	1.4	145
PSH-P140i	18	6	143	8.5	4.4	1.5	166
AHU heating and cooling							
EWWP022	4	9	56	12.5	4.1	2.0	86
EWWP045	2	5	52	12.4	4.1	2.0	81
EWWP090	1	3	43	12.3	4.1	2.0	72
EWWP120	1	2	37	12.3	4.0	1.9	66
EWWP185	1	1	27	12.3	4.0	1.9	57

Table B- 14 - Selection method of installations that provide heating and cooling for case I.3 in which supply energy is both fuel and electricity.

Case I.3 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.47	96	113	27.3	1.8	140
GB312-200+REV3.2	1.17	78	105	27.3	1.8	132
GB312-240+REV3.7	0.98	66	93	27.3	1.8	120
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	18		56	2.4	0.3	60
PSH-S50i	18		63	2.5	0.3	67
PSH-S60i	12		46	2.3	0.3	51
PSH-S71i	12		55	2.3	0.3	59
PSH-P100i	12		73	2.7	0.3	78
PSH-P125i	6		41	4.0	0.5	48
PSH-P140i	6		48	4.4	0.5	55
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.52		0	51.5	3.3	50
GB312-200	0.41		0	51.5	3.3	50
GB312-240	0.35		12	51.5	3.3	62
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.1	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 15 - Heating and cooling load for zone acclimatization and ventilation for case G.1

Load (kW)	
Zone Heating	735
ZH 0.990th quantile	268
AHU heating	92
Zone Cooling	231
ZC 0.990th quantile	40
AHU cooling	181

Table B- 16 - Heating and cooling yearly energy demand for case G.1

Energy demand (MWh)	
Zone Heating	55
Zone Cooling	10
AHU heating	70
AHU cooling	14
Total Heating	125
Total Cooling	24

Table B- 17 - Selection method of installations that provide heating and cooling for case G.1 in which supply energy is all electric.

Case G.1 – Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	12	204	13.4	1.7	1.8	231
PSH-S50i	54	12	189	13.8	1.8	1.9	217
PSH-S60i	42	12	162	13.8	1.7	1.8	190
PSH-S71i	36	6	166	13.8	1.7	1.8	193
PSH-P100i	24	6	146	14.5	2.0	2.0	175
PSH-P125i	24	6	164	14.9	2.9	2.1	196
PSH-P140i	18	6	143	15.7	3.2	2.3	177
AHU heating and cooling							
EWWP022	4	9	56	15.6	4.1	2.3	91
EWWP045	2	5	52	15.5	4.1	2.3	87
EWWP090	1	3	43	15.4	4.0	2.3	77
EWWP120	1	2	37	15.4	4.0	2.3	72
EWWP185	1	1	27	15.3	4.0	2.3	62

Table B- 18 - Selection method of installations that provide heating and cooling for G.1 in which supply energy is both fuel and electricity.

Case G.1 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.67	108	124	50.5	3.3	173
GB312-200+REV3.2	1.34	90	117	50.5	3.3	166
GB312-240+REV3.7	1.12	78	123	50.5	3.3	172
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	12		37	1.7	0.2	40
PSH-S50i	12		42	1.8	0.2	45
PSH-S60i	12		46	1.7	0.2	49
PSH-S71i	6		28	1.7	0.2	31
PSH-P100i	6		36	2.0	0.2	40
PSH-P125i	6		41	2.9	0.4	46
PSH-P140i	6		48	3.2	0.4	53
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.58		12	64.1	4.2	75
GB312-200	0.46		0	64.1	4.2	62
GB312-240	0.38		0	64.1	4.2	62
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.0	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 19 - Heating and cooling load for zone acclimatization and ventilation for case G.2

Load (kW)	
Zone Heating	664
ZH 0.990th quantile	258
AHU heating	89
Zone Cooling	241
ZC 0.990th quantile	55
AHU cooling	181

Table B- 20 - Heating and cooling yearly energy demand for case G.2

Energy demand (MWh)	
Zone Heating	45
Zone Cooling	13
AHU heating	65
AHU cooling	14
Total Heating	110
Total Cooling	27

Table B- 21 - Selection method of installations that provide heating and cooling for case G.2 in which supply energy is all electric.

Case G.2 – Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	18	204	11.0	2.1	1.6	227
PSH-S50i	48	12	168	11.2	2.2	1.6	192
PSH-S60i	42	12	162	11.2	2.1	1.6	186
PSH-S71i	36	12	166	11.2	2.1	1.6	190
PSH-P100i	24	6	146	11.8	2.5	1.7	171
PSH-P125i	24	6	164	12.2	3.6	1.9	193
PSH-P140i	18	6	143	12.9	3.9	2.0	173
AHU heating and cooling							
EWWP022	4	9	56	14.4	4.1	2.2	89
EWWP045	2	5	52	14.4	4.1	2.2	85
EWWP090	1	3	43	14.2	4.1	2.2	75
EWWP120	1	2	37	14.2	4.0	2.2	70
EWWP185	1	1	27	14.2	4.0	2.2	60

Table B- 22 - Selection method of installations that provide heating and cooling for G.2 in which supply energy is both fuel and electricity.

Case G.2 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.62	102	119	41.3	2.7	159
GB312-200+REV3.2	1.29	84	111	41.3	2.7	151
GB312-240+REV3.7	1.08	72	116	41.3	2.7	156
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	18		56	2.1	0.3	59
PSH-S50i	12		42	2.2	0.3	46
PSH-S60i	12		46	2.1	0.3	50
PSH-S71i	12		55	2.1	0.3	59
PSH-P100i	6		36	2.5	0.3	41
PSH-P125i	6		41	3.6	0.4	48
PSH-P140i	6		48	3.9	0.5	55
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.56		12	59.5	3.9	70
GB312-200	0.45		0	59.5	3.9	58
GB312-240	0.37		0	59.5	3.9	58
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.1	0.5	63
EWWP045	5		52	4.1	0.5	59
EWWP090	3		43	4.1	0.5	50
EWWP120	2		37	4.0	0.5	44
EWWP185	1		27	4.0	0.5	35

Table B- 23 - Heating and cooling load for zone acclimatization and ventilation for case W20

Load (kW)	
Zone Heating	767
ZH 0.990th quantile	291
AHU heating	94
Zone Cooling	126
ZC 0.990th quantile	0
AHU cooling	185

Table B- 24 - Heating and cooling yearly energy demand for case W20

Energy demand (MWh)	
Zone Heating	74
Zone Cooling	2
AHU heating	77
AHU cooling	13
Total Heating	151
Total Cooling	15

Table B- 25 - Selection method of installations that provide heating and cooling for case W20 in which supply energy is all electric.

Case W20 – Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	72	0	222	18.0	0.3	2.2	255
PSH-S50i	54	0	189	18.4	0.3	2.2	222
PSH-S60i	48	0	186	18.4	0.3	2.2	219
PSH-S71i	42	0	193	18.4	0.3	2.2	227
PSH-P100i	30	0	182	19.4	0.4	2.3	217
PSH-P125i	24	0	164	19.9	0.5	2.4	201
PSH-P140i	24	0	191	21.0	0.6	2.6	229
AHU heating and cooling							
EWWP022	4	9	56	17.2	3.8	2.5	93
EWWP045	2	5	52	17.1	3.8	2.5	89
EWWP090	1	3	43	17.0	3.7	2.5	80
EWWP120	1	2	37	16.9	3.7	2.5	74
EWWP185	1	1	27	16.9	3.7	2.5	64

Table B- 26 - Selection method of installations that provide heating and cooling for W20 in which supply energy is both fuel and electricity.

Case W20 – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.82	114	130	67.5	4.4	196
GB312-200+REV3.2	1.45	96	123	67.5	4.4	189
GB312-240+REV3.7	1.21	84	130	67.5	4.4	195
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	0		0	0	0	0
PSH-S50i	0		0	0	0	0
PSH-S60i	0		0	0	0	0
PSH-S71i	0		0	0	0	0
PSH-P100i	0		0	0	0	0
PSH-P125i	0		0	0	0	0
PSH-P140i	0		0	0	0	0
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.59		12	70.8	4.6	81
GB312-200	0.47		0	70.8	4.6	69
GB312-240	0.39		0	70.8	4.6	69
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	3.8	0.5	63
EWWP045	5		52	3.8	0.4	58
EWWP090	3		43	3.7	0.4	49
EWWP120	2		37	3.7	0.4	44
EWWP185	1		27	3.7	0.4	34

Table B- 27 - Heating and cooling load for zone acclimatization and ventilation for case W80

Load (kW)	
Zone Heating	643
ZH 0.990th quantile	269
AHU heating	96
Zone Cooling	643
ZC 0.990th quantile	193
AHU cooling	173

Table B- 28 - Heating and cooling yearly energy demand for case W80

Energy demand (MWh)	
Zone Heating	55
Zone Cooling	53
AHU heating	70
AHU cooling	14
Total Heating	125
Total Cooling	67

Table B- 29 - Selection method of installations that provide heating and cooling for case W80 in which supply energy is all electric.

Case W80 - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	54	204	13.4	8.9	2.7	244
PSH-S50i	54	42	189	13.7	9.2	2.7	230
PSH-S60i	42	36	162	13.7	8.8	2.7	202
PSH-S71i	36	30	166	13.7	8.8	2.7	206
PSH-P100i	24	24	146	14.4	10.3	2.9	190
PSH-P125i	24	18	164	14.8	15.1	3.6	218
PSH-P140i	18	18	143	15.7	16.5	3.8	200
AHU heating and cooling							
EWWP022	4	9	56	15.5	4.0	2.3	91
EWWP045	2	5	52	15.4	4.0	2.3	86
EWWP090	1	3	43	15.3	4.0	2.3	77
EWWP120	1	2	37	15.3	3.9	2.3	71
EWWP185	1	1	27	15.3	3.9	2.3	62

Table B- 30 - Selection method of installations that provide heating and cooling for W80 in which supply energy is both fuel and electricity.

Case W80 - Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.68	108	124	50.3	3.3	173
GB312-200+REV3.2	1.34	90	117	50.3	3.3	166
GB312-240+REV3.7	1.12	78	123	50.3	3.3	172
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	54		167	8.9	1.1	183
PSH-S50i	42		147	9.2	1.1	163
PSH-S60i	36		139	8.8	1.0	155
PSH-S71i	30		138	8.8	1.0	154
PSH-P100i	24		146	10.3	1.2	164
PSH-P125i	18		123	15.1	1.8	150
PSH-P140i	18		143	16.5	1.9	173
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.60		12	63.9	4.2	74
GB312-200	0.48		0	63.9	4.2	62
GB312-240	0.40		0	63.9	4.2	62
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.0	0.5	63
EWWP045	5		52	4.0	0.5	59
EWWP090	3		43	4.0	0.5	50
EWWP120	2		37	3.9	0.5	44
EWWP185	1		27	3.9	0.5	34

Table B- 31 - Heating and cooling load for zone acclimatization and ventilation for case G_L

Load (kW)	
Zone Heating	862
ZH 0.990th quantile	274
AHU heating	89
Zone Cooling	265
ZC 0.990th quantile	74
AHU cooling	214

Table B- 32 - Heating and cooling yearly energy demand for case G_L

Energy demand (MWh)	
Zone Heating	60
Zone Cooling	16
AHU heating	62
AHU cooling	23
Total Heating	122
Total Cooling	39

Table B- 33 - Selection method of installations that provide heating and cooling for case G_L in which supply energy is all electric.

Case G_L - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	72	24	222	14.7	2.8	2.1	254
PSH-S50i	54	18	189	15.0	2.9	2.1	221
PSH-S60i	42	18	162	15.0	2.7	2.1	194
PSH-S71i	36	12	166	15.0	2.7	2.1	197
PSH-P100i	30	12	182	15.8	3.2	2.3	216
PSH-P125i	24	12	164	16.2	4.7	2.5	202
PSH-P140i	18	6	143	17.2	5.1	2.6	183
AHU heating and cooling							
EWWP022	4	11	68	13.7	6.6	2.4	105
EWWP045	2	6	62	13.6	6.5	2.4	98
EWWP090	1	3	43	13.5	6.5	2.4	78
EWWP120	1	2	37	13.5	6.4	2.4	73
EWWP185	1	2	55	13.5	6.4	2.4	90

Table B- 34 - Selection method of installations that provide heating and cooling for G_L in which supply energy is both fuel and electricity.

Case G_L - Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.71	108	124	55.1	3.6	178
GB312-200+REV3.2	1.37	90	117	55.1	3.6	171
GB312-240+REV3.7	1.14	78	123	55.1	3.6	176
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	24		74	2.8	0.3	79
PSH-S50i	18		63	2.9	0.3	68
PSH-S60i	18		70	2.7	0.3	74
PSH-S71i	12		55	2.7	0.3	60
PSH-P100i	12		73	3.2	0.4	79
PSH-P125i	12		82	4.7	0.6	91
PSH-P140i	6		48	5.1	0.6	57
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.56		12	56.4	3.7	67
GB312-200	0.45		0	56.4	3.7	55
GB312-240	0.37		0	56.4	3.7	55
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	11		68	6.6	0.8	80
EWWP045	6		62	6.5	0.8	74
EWWP090	3		43	6.5	0.8	54
EWWP120	2		37	6.4	0.8	49
EWWP185	2		55	6.4	0.8	66

Table B- 35 - Heating and cooling load for zone acclimatization and ventilation for case W_H

Load (kW)	
Zone Heating	415
ZH 0.990th quantile	270
AHU heating	83
Zone Cooling	302
ZC 0.990th quantile	134
AHU cooling	261

Table B- 36 - Heating and cooling yearly energy demand for case W_H

Energy demand (MWh)	
Zone Heating	56
Zone Cooling	32
AHU heating	47
AHU cooling	40
Total Heating	103
Total Cooling	72

Table B- 37 - Selection method of installations that provide heating and cooling for case W_H in which supply energy is all electric.

Case W_H - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	42	204	13.6	5.4	2.3	238
PSH-S50i	54	30	189	13.9	5.6	2.3	223
PSH-S60i	42	24	162	13.9	5.3	2.3	197
PSH-S71i	36	24	166	13.9	5.3	2.3	200
PSH-P100i	30	18	182	14.6	6.2	2.5	219
PSH-P125i	24	12	164	15.0	9.1	2.9	207
PSH-P140i	18	12	143	15.9	9.9	3.1	189
AHU heating and cooling							
EWWP022	4	13	81	10.5	11.5	2.6	120
EWWP045	2	7	72	10.5	11.4	2.6	112
EWWP090	1	4	57	10.4	11.3	2.6	96
EWWP120	1	3	56	10.4	11.3	2.6	94
EWWP185	1	2	55	10.4	11.3	2.6	93

Table B- 38 - Selection method of installations that provide heating and cooling for W_H in which supply energy is both fuel and electricity.

Case W_H - Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.69	108	124	51.0	3.3	174
GB312-200+REV3.2	1.35	90	117	51.0	3.3	167
GB312-240+REV3.7	1.13	78	123	51.0	3.3	172
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	42		130	5.4	0.6	139
PSH-S50i	30		105	5.6	0.7	115
PSH-S60i	24		93	5.3	0.6	102
PSH-S71i	24		111	5.3	0.6	120
PSH-P100i	18		109	6.2	0.7	120
PSH-P125i	12		82	9.1	1.1	98
PSH-P140i	12		95	9.9	1.2	113
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.52		12	43.4	2.8	54
GB312-200	0.41		0	43.4	2.8	42
GB312-240	0.35		0	43.4	2.8	42
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	13		81	11.5	1.4	101
EWWP045	7		72	11.4	1.4	93
EWWP090	4		57	11.3	1.4	77
EWWP120	3		56	11.3	1.3	76
EWWP185	2		55	11.3	1.3	75

Table B- 39 - Heating and cooling load for zone acclimatization and ventilation for case SB

Load (kW)	
Zone Heating	475
ZH 0.990th quantile	292
AHU heating	99
Zone Cooling	204
ZC 0.990th quantile	7
AHU cooling	184

Table B- 40 - Heating and cooling yearly energy demand for case SB

Energy demand (MWh)	
Zone Heating	74
Zone Cooling	6
AHU heating	79
AHU cooling	14
Total Heating	153
Total Cooling	20

Table B- 41 - Selection method of installations that provide heating and cooling for case SB in which supply energy is all electric.

Case SB - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	72	6	222	18.2	1.1	2.3	257
PSH-S50i	54	6	189	18.6	1.1	2.3	224
PSH-S60i	48	6	186	18.6	1.1	2.3	221
PSH-S71i	42	6	193	18.6	1.1	2.3	229
PSH-P100i	30	6	182	19.6	1.2	2.5	219
PSH-P125i	24	6	164	20.1	1.8	2.6	204
PSH-P140i	24	6	191	21.3	2.0	2.8	232
AHU heating and cooling							
EWWP022	4	9	56	17.5	4.0	2.6	94
EWWP045	2	5	52	17.5	4.0	2.6	90
EWWP090	1	3	43	17.3	4.0	2.5	81
EWWP120	1	2	37	17.3	3.9	2.5	75
EWWP185	1	1	27	17.3	3.9	2.5	65

Table B- 42 - Selection method of installations that provide heating and cooling for SB in which supply energy is both fuel and electricity.

Case SB – Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.82	114	130	68.3	4.4	196
GB312-200+REV3.2	1.46	96	123	68.3	4.4	189
GB312-240+REV3.7	1.22	84	130	68.3	4.4	196
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	6		19	1.1	0.1	20
PSH-S50i	6		21	1.1	0.1	23
PSH-S60i	6		23	1.1	0.1	25
PSH-S71i	6		28	1.1	0.1	30
PSH-P100i	6		36	1.2	0.1	39
PSH-P125i	6		41	1.8	0.2	44
PSH-P140i	6		48	2.0	0.2	51
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160	0.62		12	72.3	4.7	83
GB312-200	0.49		0	72.3	4.7	70
GB312-240	0.41		0	72.3	4.7	70
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	9		56	4.0	0.5	63
EWWP045	5		52	4.0	0.5	59
EWWP090	3		43	4.0	0.5	50
EWWP120	2		37	3.9	0.5	44
EWWP185	1		27	3.9	0.5	34

Table B- 43 - Heating and cooling load for zone acclimatization and ventilation for combination case

Load (kW)	
Zone Heating	780
ZH 0.990th quantile	250
AHU heating	84
Zone Cooling	248
ZC 0.990th quantile	68
AHU cooling	215

Table B- 44 - Heating and cooling yearly energy demand for combination case

Energy demand (MWh)	
Zone Heating	39
Zone Cooling	15
AHU heating	52
AHU cooling	23
Total Heating	91
Total Cooling	38

Table B- 45 - Selection method of installations that provide heating and cooling for combination case in which supply energy is all electric.

Combination case - Option 1: Heating Electric + Cooling Electric							
Zone heating and cooling							
Model	Nr Heating units	Nr Cooling Units	Invest Equip (t €)	Elec heating (MWh)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	66	24	204	9.5	2.5	1.4	225
PSH-S50i	48	18	168	9.7	2.6	1.5	190
PSH-S60i	42	12	162	9.7	2.4	1.4	184
PSH-S71i	36	12	166	9.7	2.4	1.4	187
PSH-P100i	24	12	146	10.2	2.9	1.6	169
PSH-P125i	18	6	123	10.5	4.2	1.7	150
PSH-P140i	18	6	143	11.1	4.6	1.9	171
AHU heating and cooling							
EWWP022	4	11	68	11.5	6.5	2.1	101
EWWP045	2	6	62	11.5	6.5	2.1	94
EWWP090	1	3	43	11.4	6.4	2.1	74
EWWP120	1	2	37	11.4	6.4	2.1	69
EWWP185	1	2	55	11.4	6.4	2.1	86

Table B- 46 - Selection method of installations that provide heating and cooling for combination case in which supply energy is both fuel and electricity.

Combination Case - Option 2: Heating Fuel + Cooling Electric						
Zone heating						
Model	Nr Boilers	Nr Radiators	Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
GB312-160+REV2.6	1.57	102	119	35.6	2.3	153
GB312-200+REV3.2	1.25	84	111	35.6	2.3	146
GB312-240+REV3.7	1.04	72	116	35.6	2.3	150
Zone cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
PSH-S35i	24		74	2.5	0.3	79
PSH-S50i	18		63	2.6	0.3	67
PSH-S60i	12		46	2.4	0.3	51
PSH-S71i	12		55	2.4	0.3	60
PSH-P100i	12		73	2.9	0.3	78
PSH-P125i	6		41	4.2	0.5	49
PSH-P140i	6		48	4.6	0.5	56
AHU heating						
Model	Nr Boilers		Invest Equip (t €)	Fuel heating (MWh)	Annual En cost (t €)	Lifetime cost (t €)
Log plus GB312-160	0.53		12	47.5	3.1	58
Log plus GB312-200	0.42		0	47.5	3.1	46
Log plus GB312-240	0.35		0	47.5	3.1	46
AHU cooling						
Model	Nr Cooling Units		Invest Equip (t €)	Elec cooling (MWh)	Annual En cost (t €)	Lifetime cost (t €)
EWWP022	11		68	6.5	0.8	80
EWWP045	6		62	6.5	0.8	74
EWWP090	3		43	6.4	0.8	54
EWWP120	2		37	6.4	0.8	49
EWWP185	2		55	6.4	0.8	66

C: Investment on materials

Table C- 1 - Area of insulated surfaces for the reference and insulation cases

Insulation	
Constructions with insulation	**Area (m^2)**
External wall	2,055
External floor	1,600
Internal floor	1,600
Roof	1,619

Table C- 2 - Investment on insulation for the reference and each insulation case according to the type of construction

Investment on insulation				
Construction	**Price (t €)**			
	Reference	Case I.1	Case I.2	Case I.3
External wall	30	51	62	77
External floor	20	29	45	53
Internal floor	15	30	37	73
Roof	29	47	65	65
Total	95	158	210	269

Table C- 3 - Area of glazed surfaces for the reference and glazing cases

Glazing	
Type of glass	**Area (m^2)**
Ground floor	207
Other floors	1,086

Table C- 4 - Investment on glass for the reference and each glazing case according to the type of construction

Investment on glazing			
Construction	**Price (t €)**		
	Reference	Case G.1	Case G.2
Glass ground floor	19	20	26
Glass other floors	123	131	164
Total	142	151	190